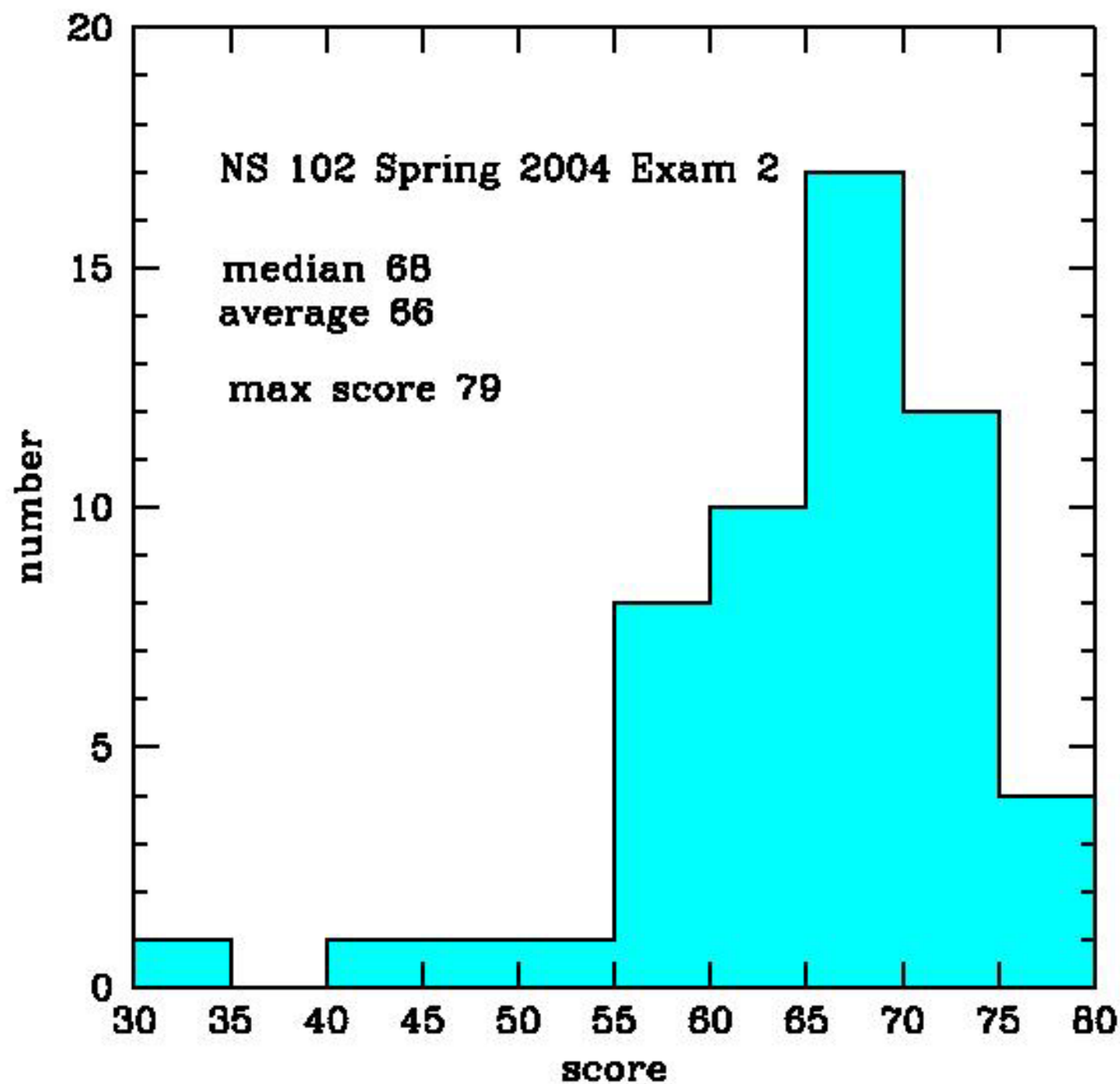


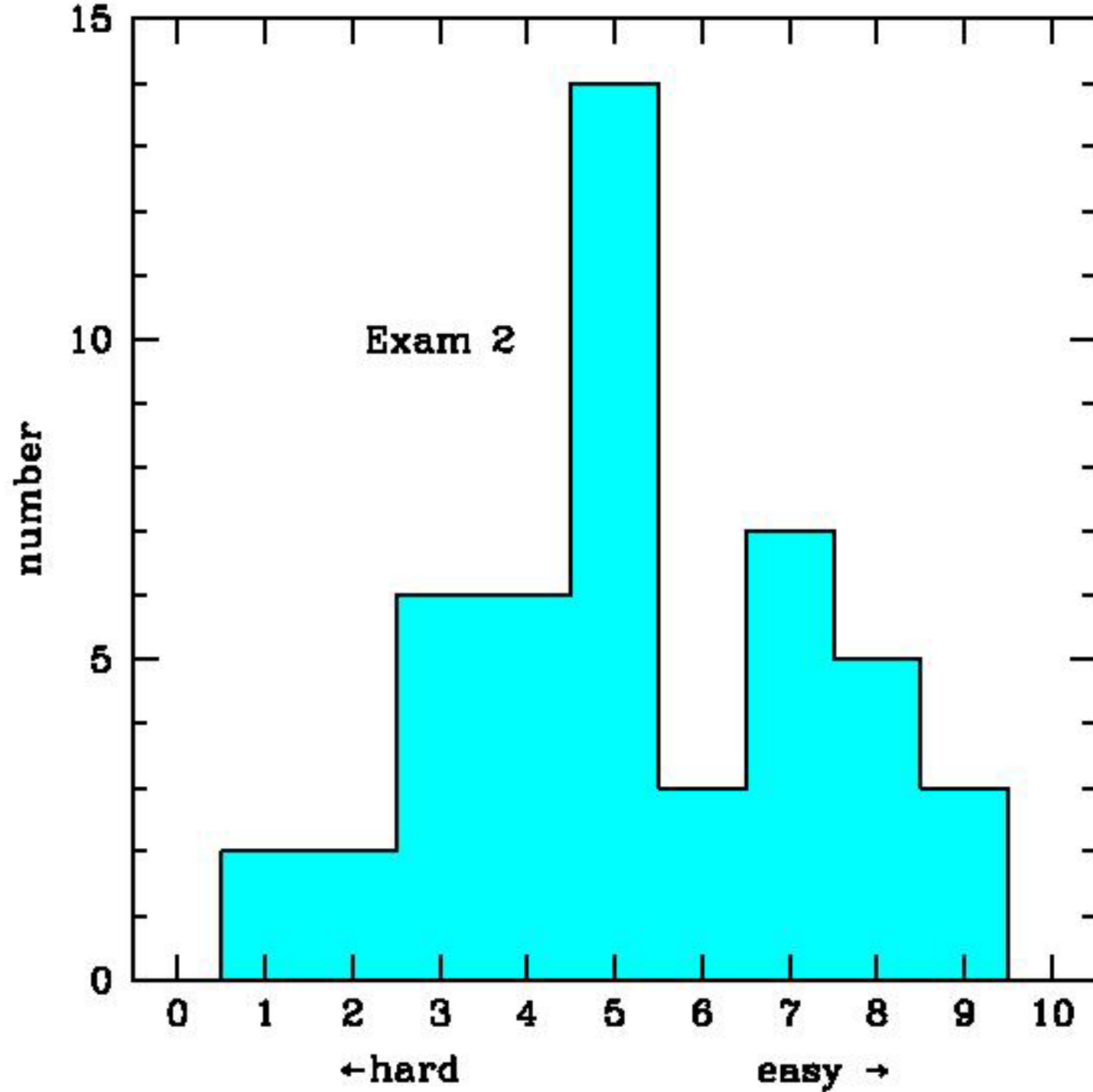
Lecture 15 May 25, 2003

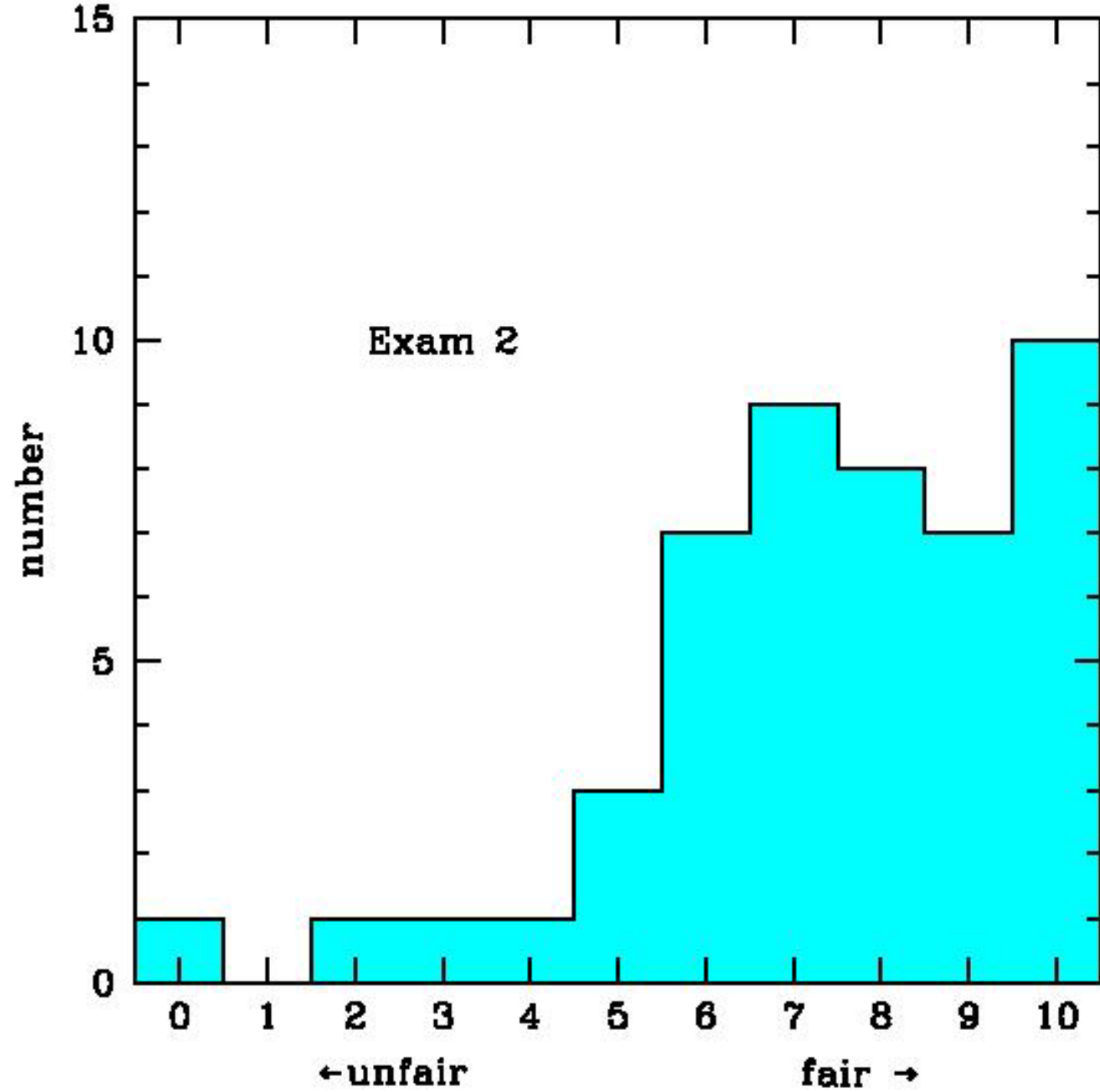
What is the Universe made of?

News of the week

- Regular office hours Tuesday & Thursday (next week also)
- Lab this week: The mass density of the Universe
- Finish reading Hawking
- Lectures:
 - May 25th: What is the Universe made of?
 - May 27th: The first second.
 - June 1st: It's about time.
- Final Exam: Tuesday, June 8th, 10:30am-12:30pm
- Sarah Stein (graduating student) please see me.





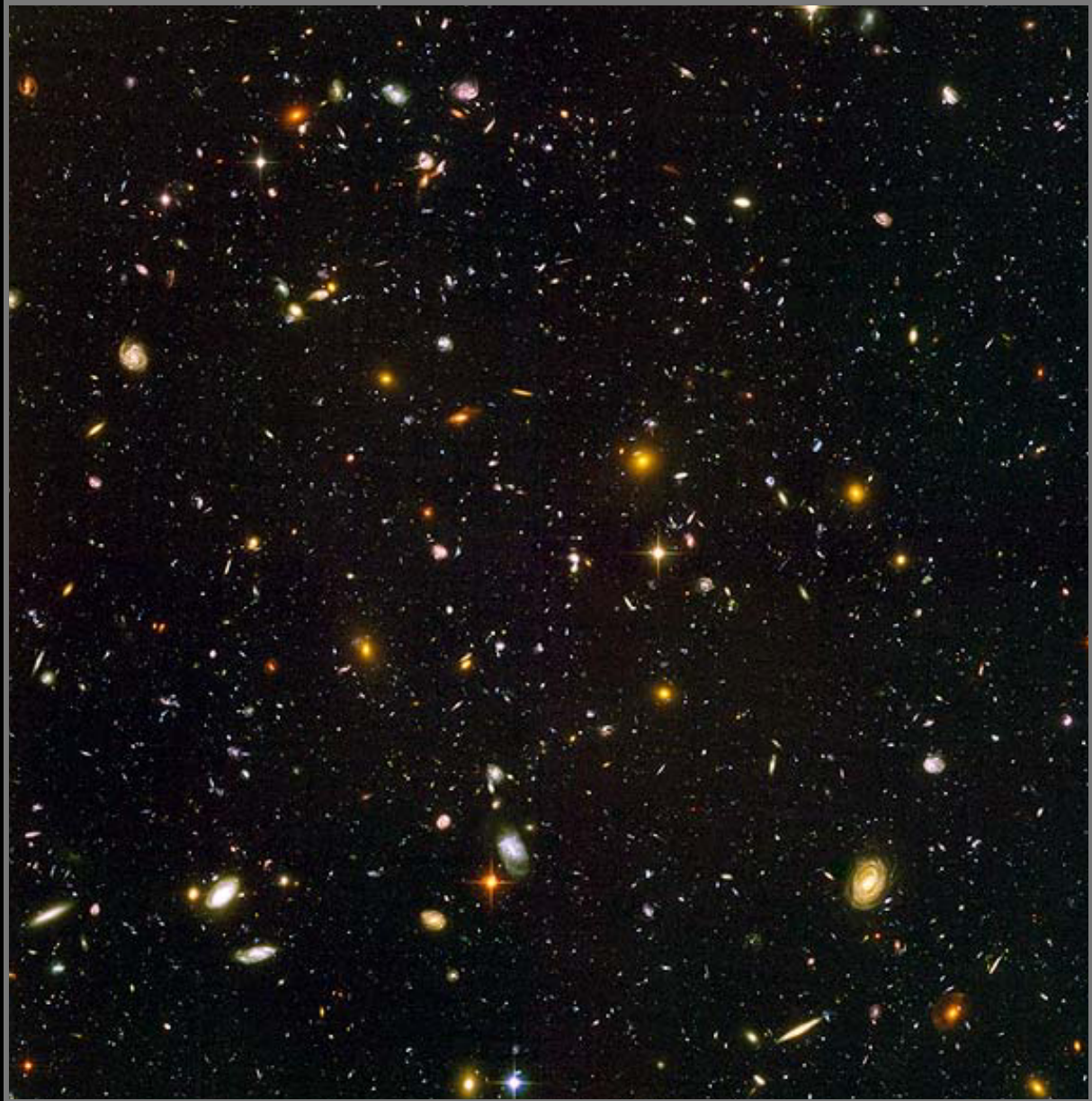


The Hubble Ultra Deep Field

UNIVERSE
OF
GALAXIES

3000
here →

50 billion
over entire
sky



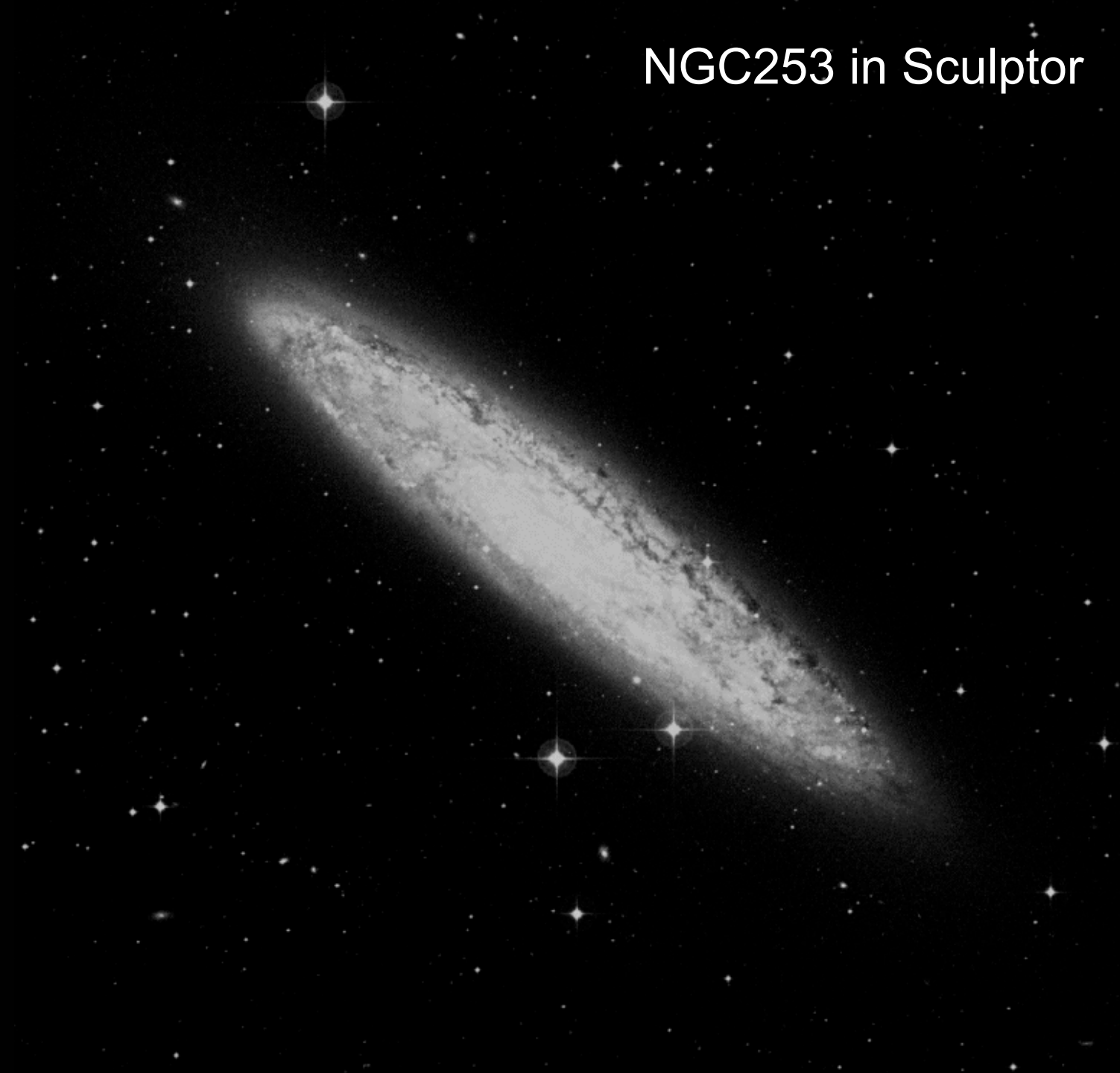
The visible universe

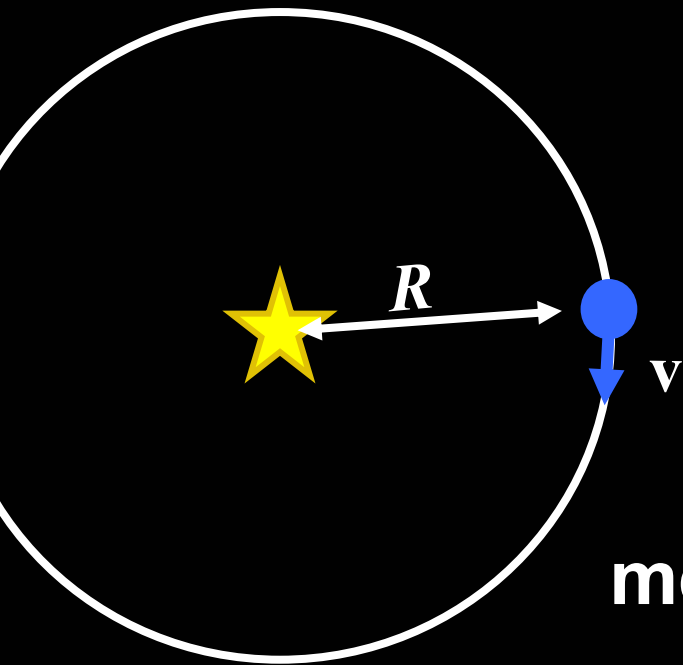


M63

Galaxies

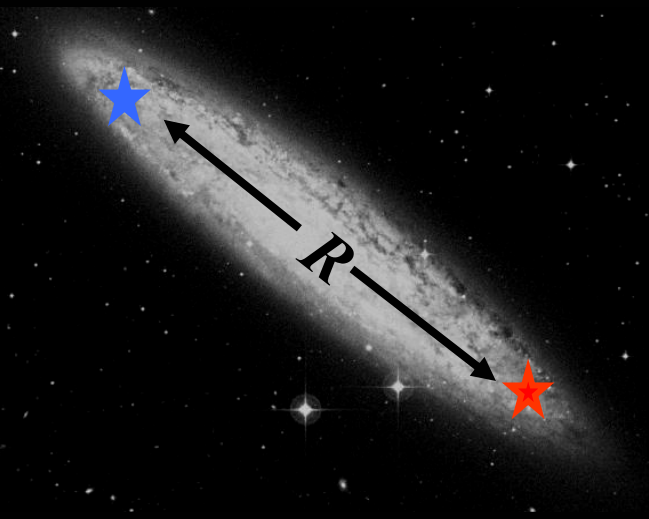
NGC253 in Sculptor





$$\frac{v^2}{R} = \frac{GM_{SUN}}{R^2}$$

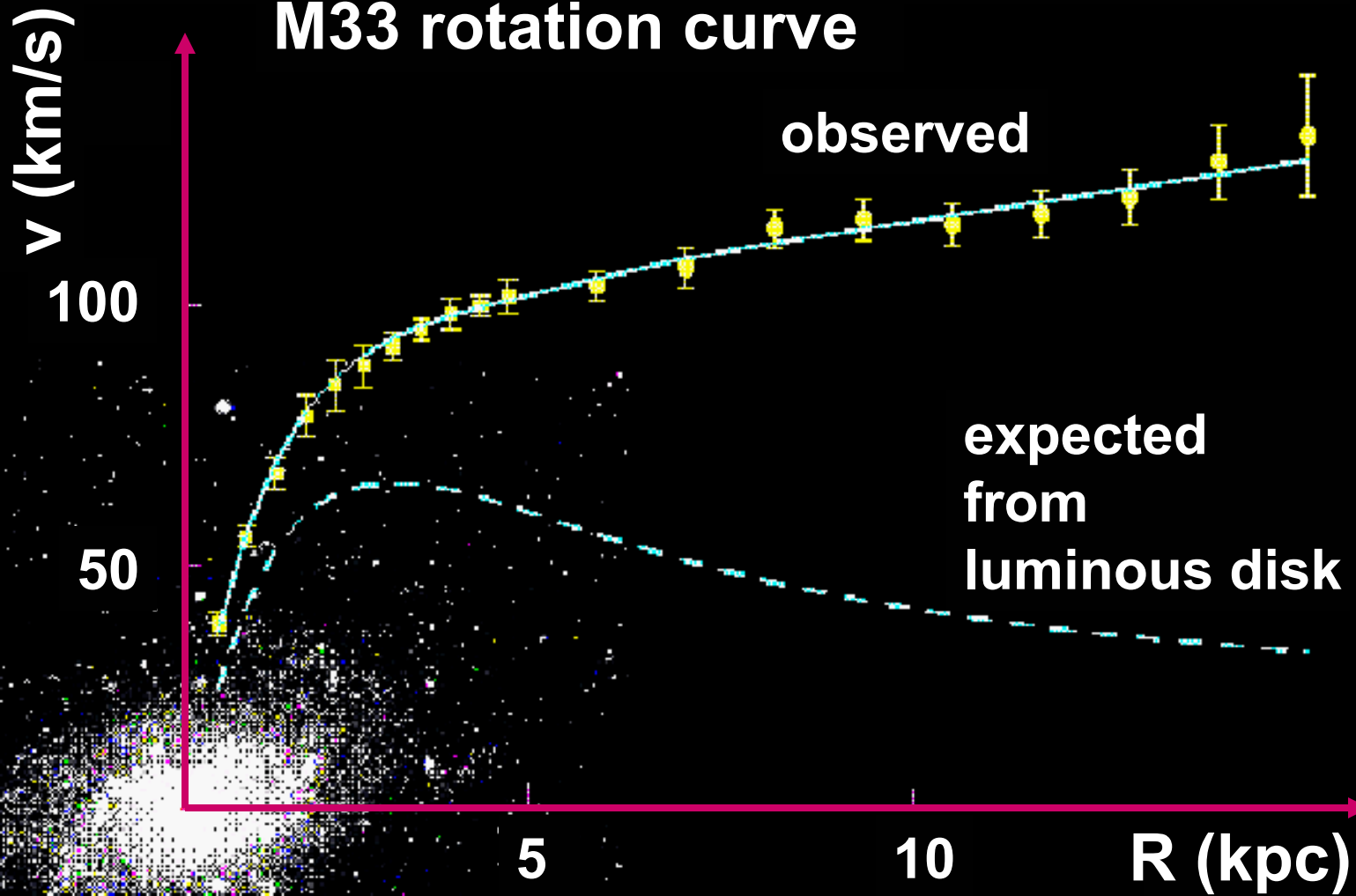
measure v & R  M_{SUN}



$$\frac{v^2}{R} = \frac{GM_{GALAXY}}{R^2}$$

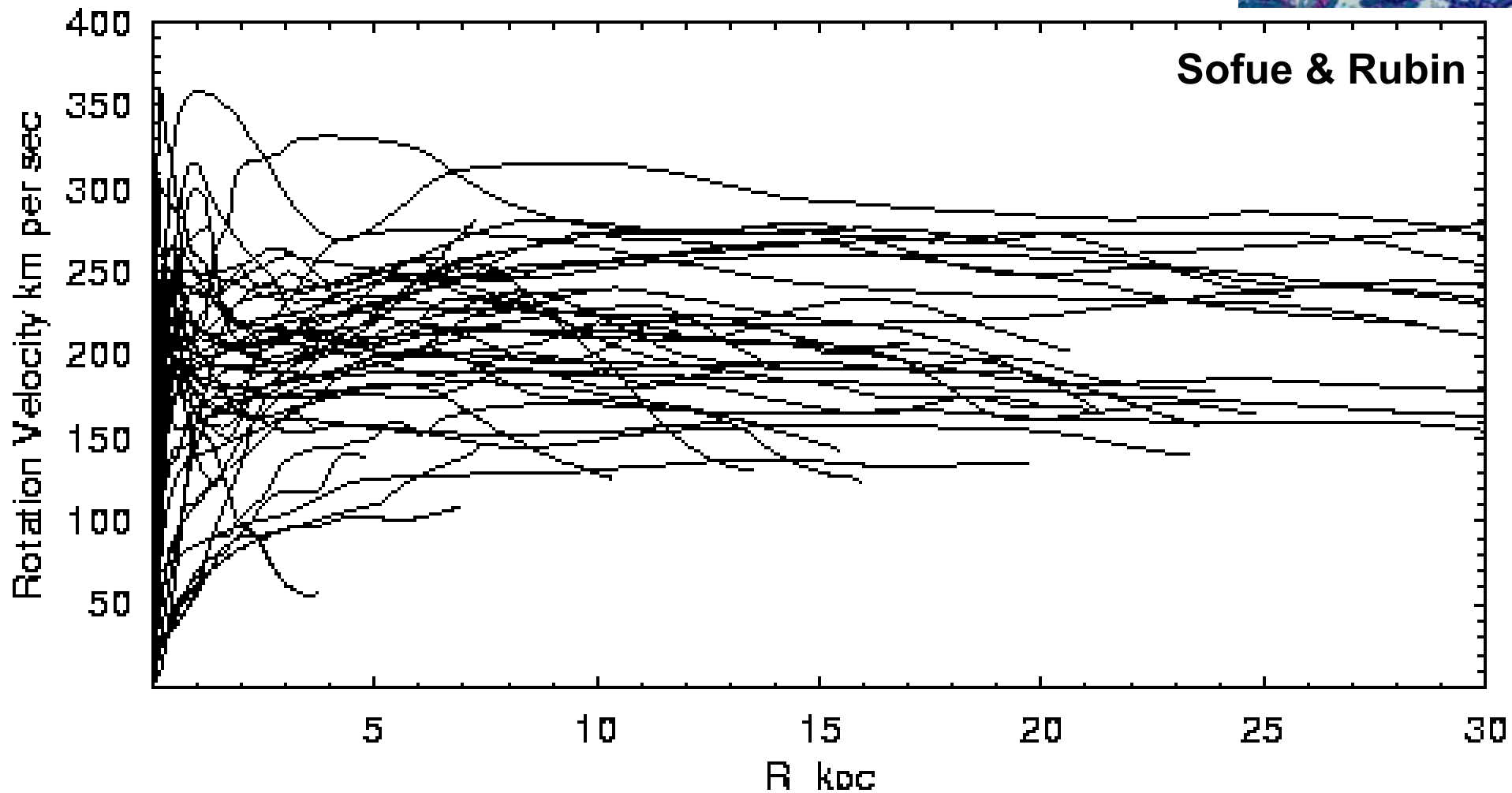
measure v & R  M_{GALAXY}

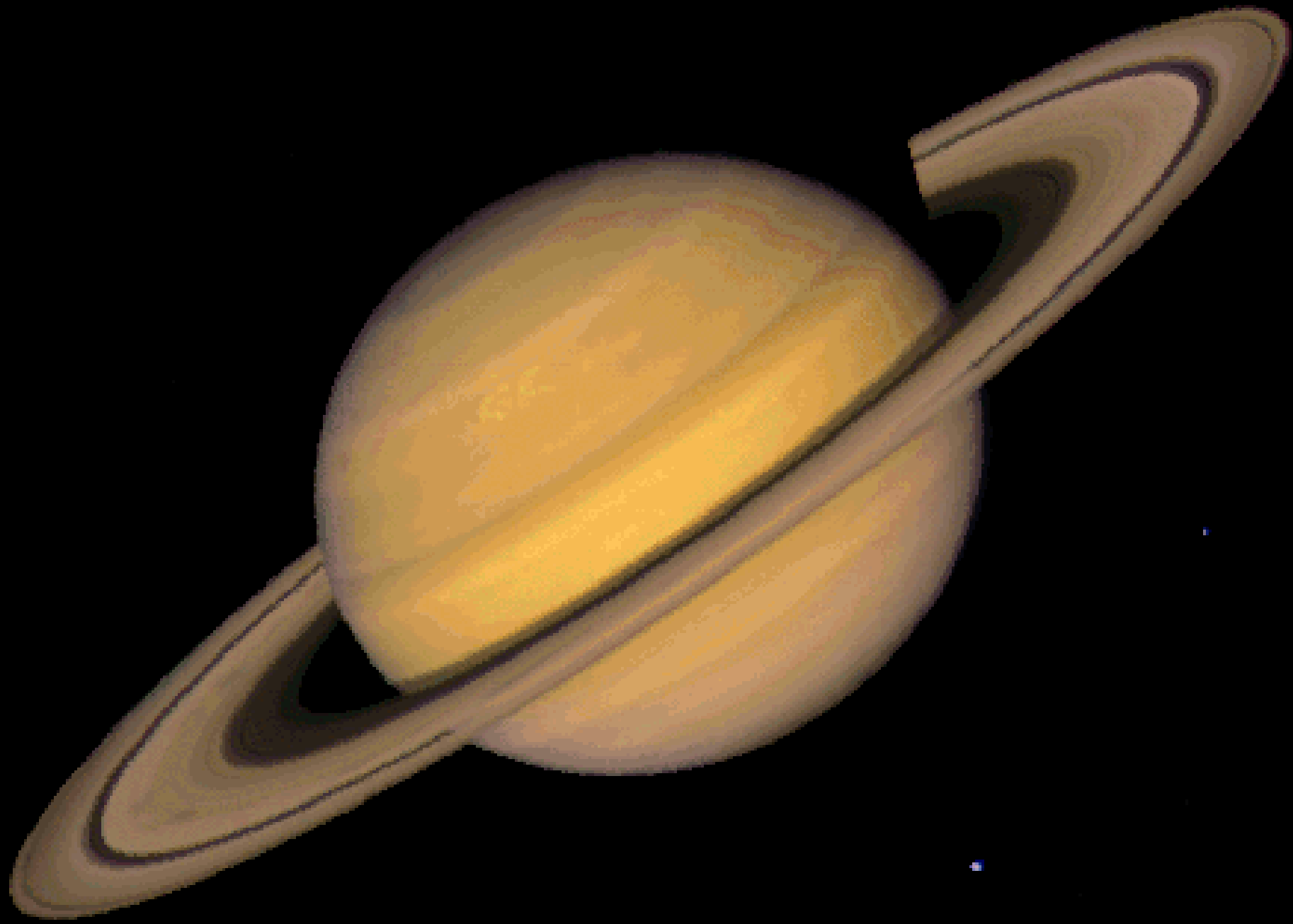
M33 rotation curve

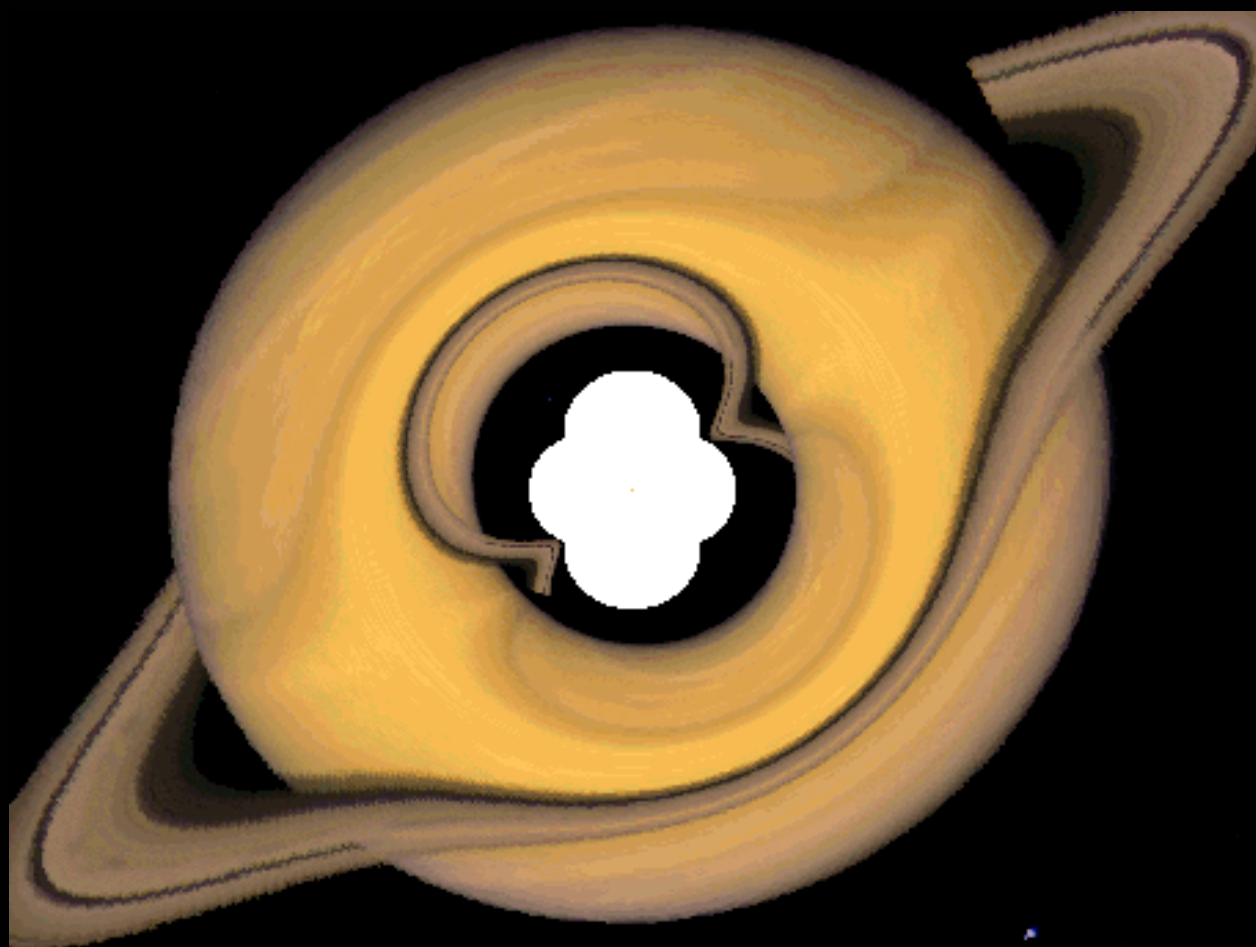


- galaxy & cluster dynamics
- gravitational lensing
- structure formation
- CMB observations

Rotation curves









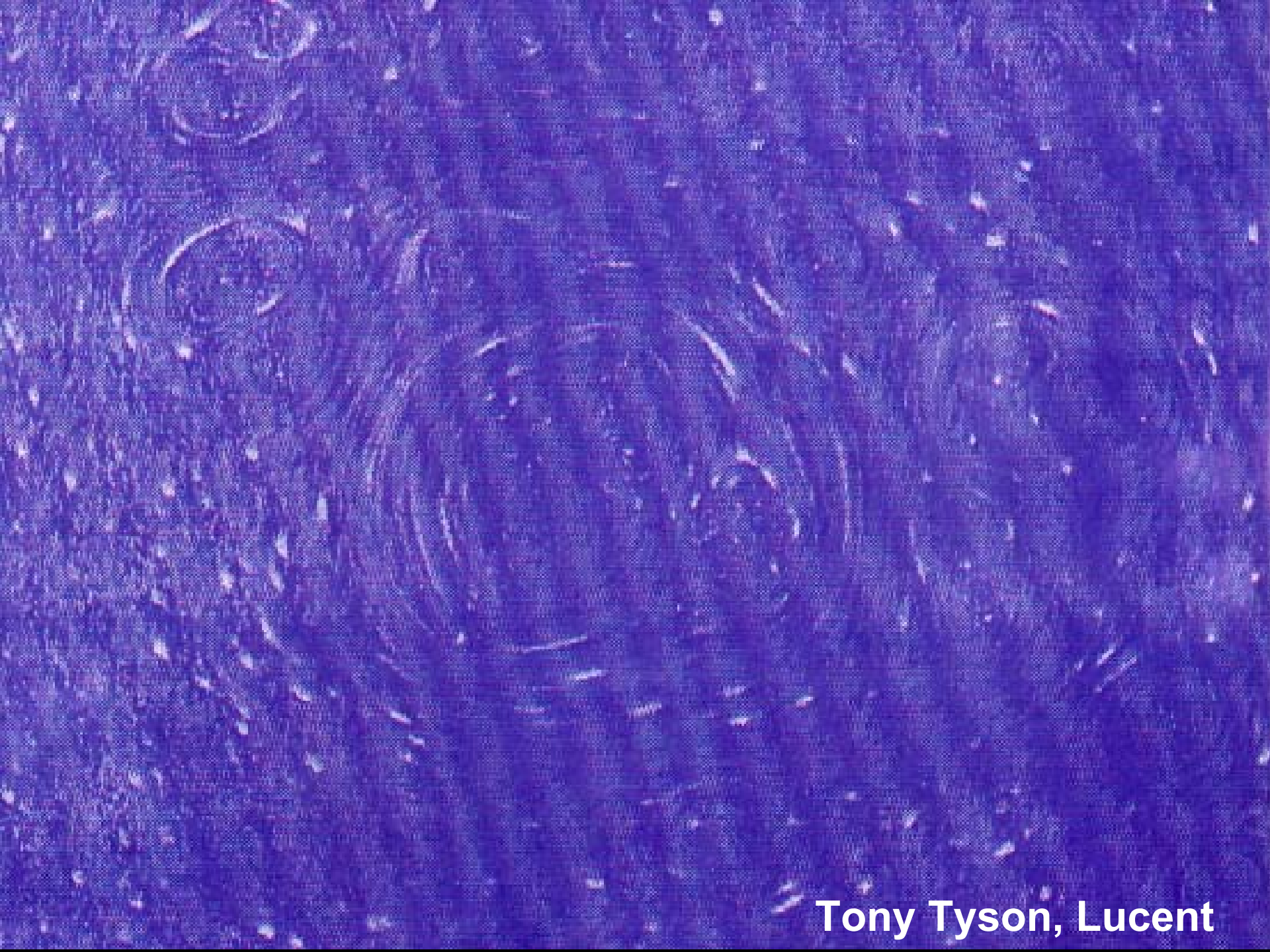
Gravitational Lens in Abell 2218

HST • WFPC2

PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA



Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

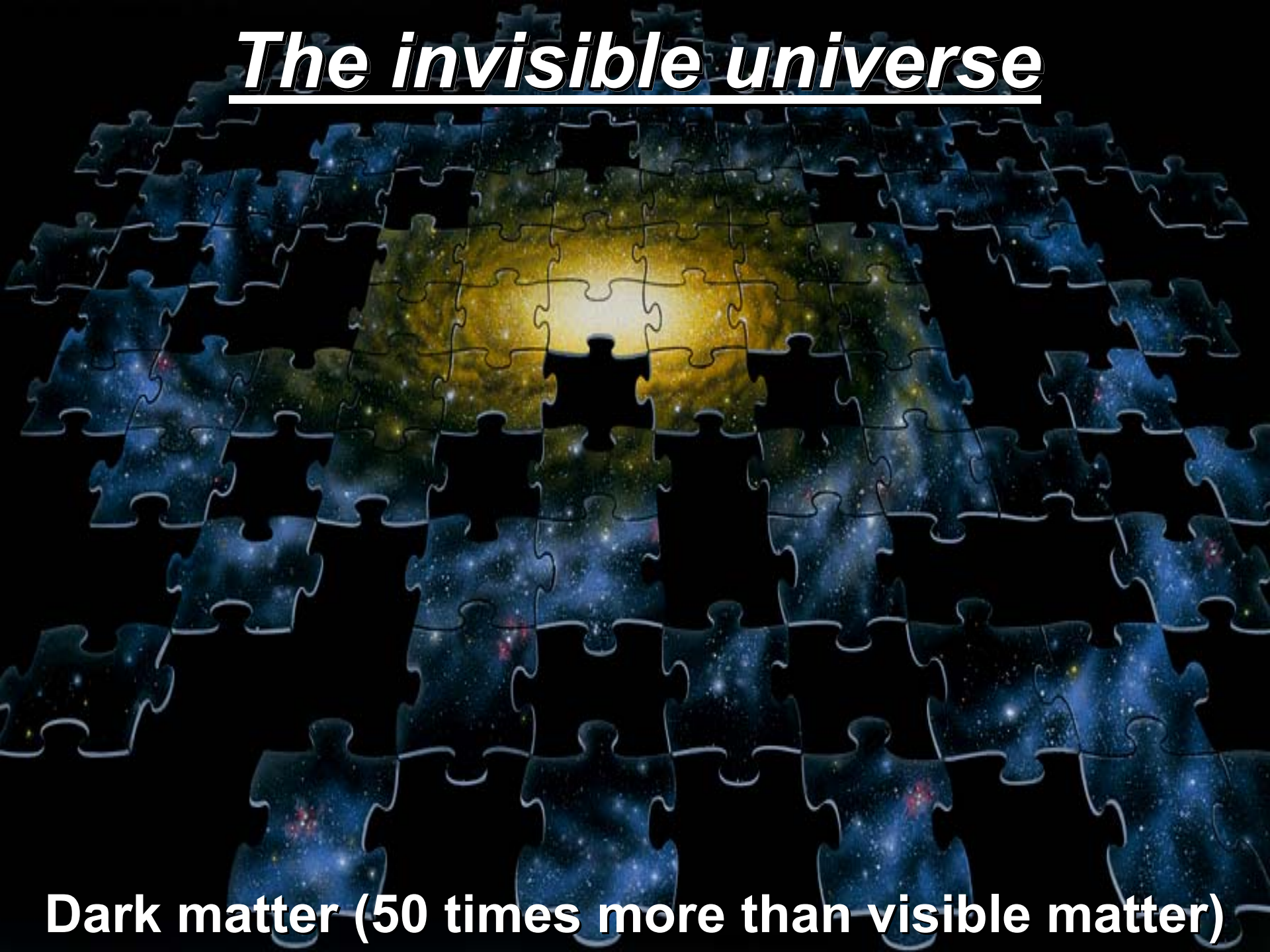


Tony Tyson, Lucent



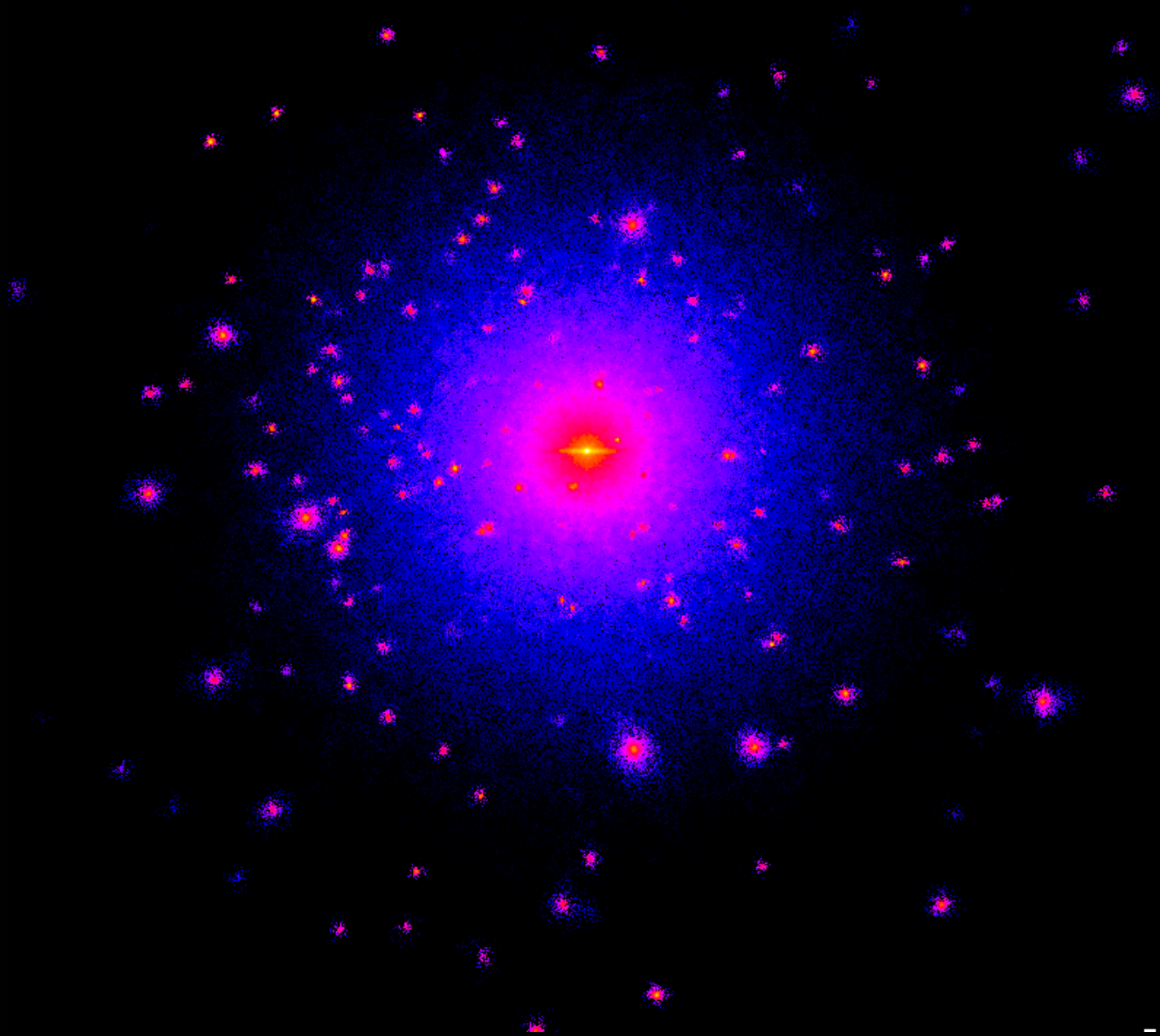
Most of the universe is dark!

The invisible universe

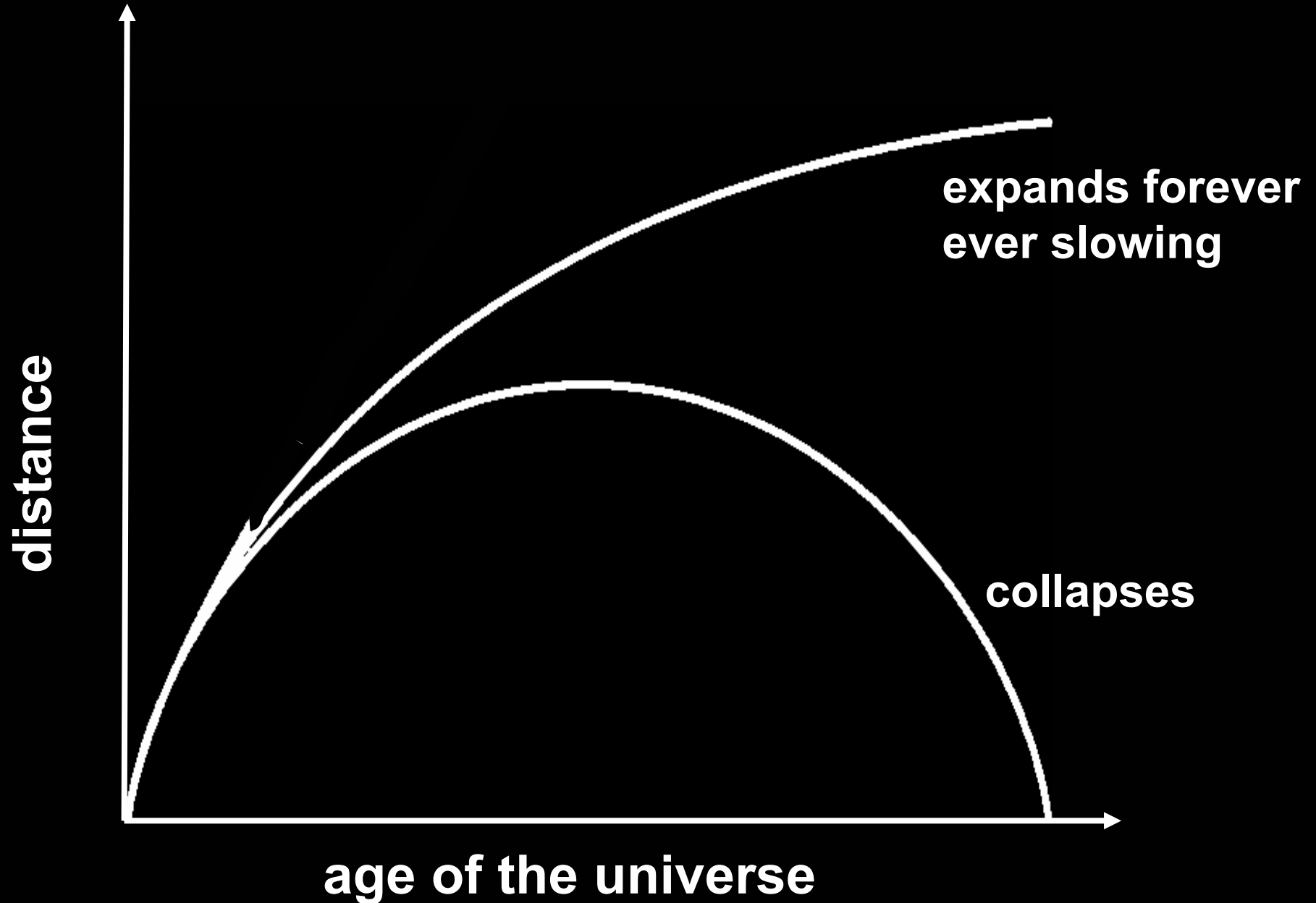


Dark matter (50 times more than visible matter)

If we could “see” dark matter



The critical density



The cosmic food chain (Ω_i)

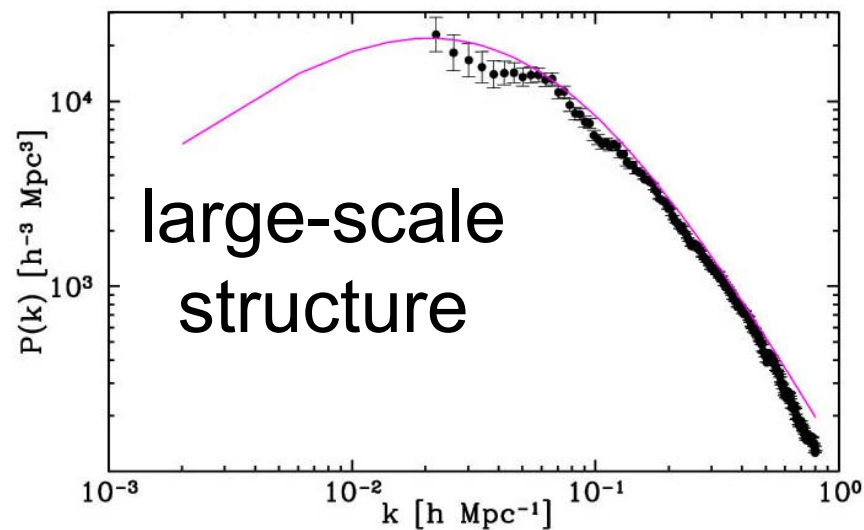
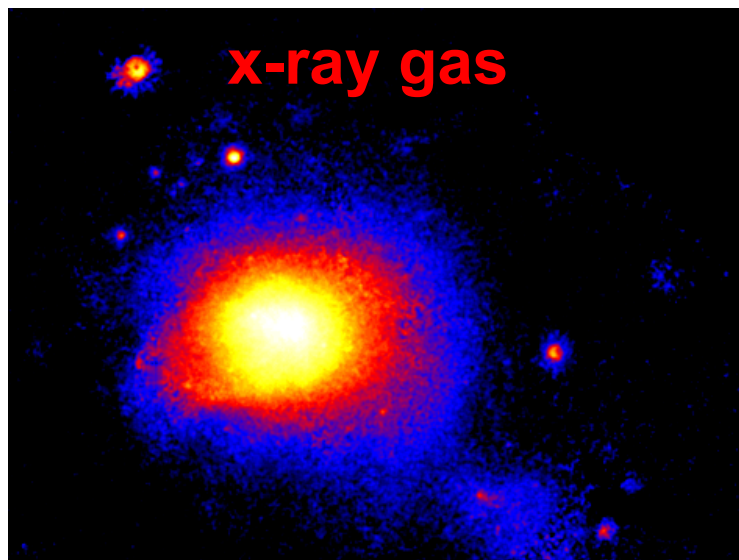
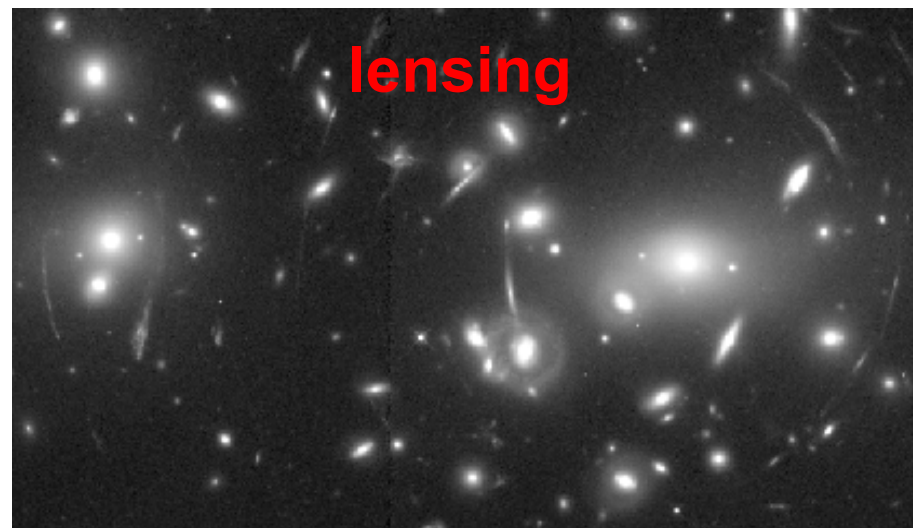
- **The critical density:**

$$\rho_c = \frac{3H_0^2}{8\pi G} \simeq 10^{-30} \text{ g cm}^{-3}$$

- **Fraction of the critical density:**

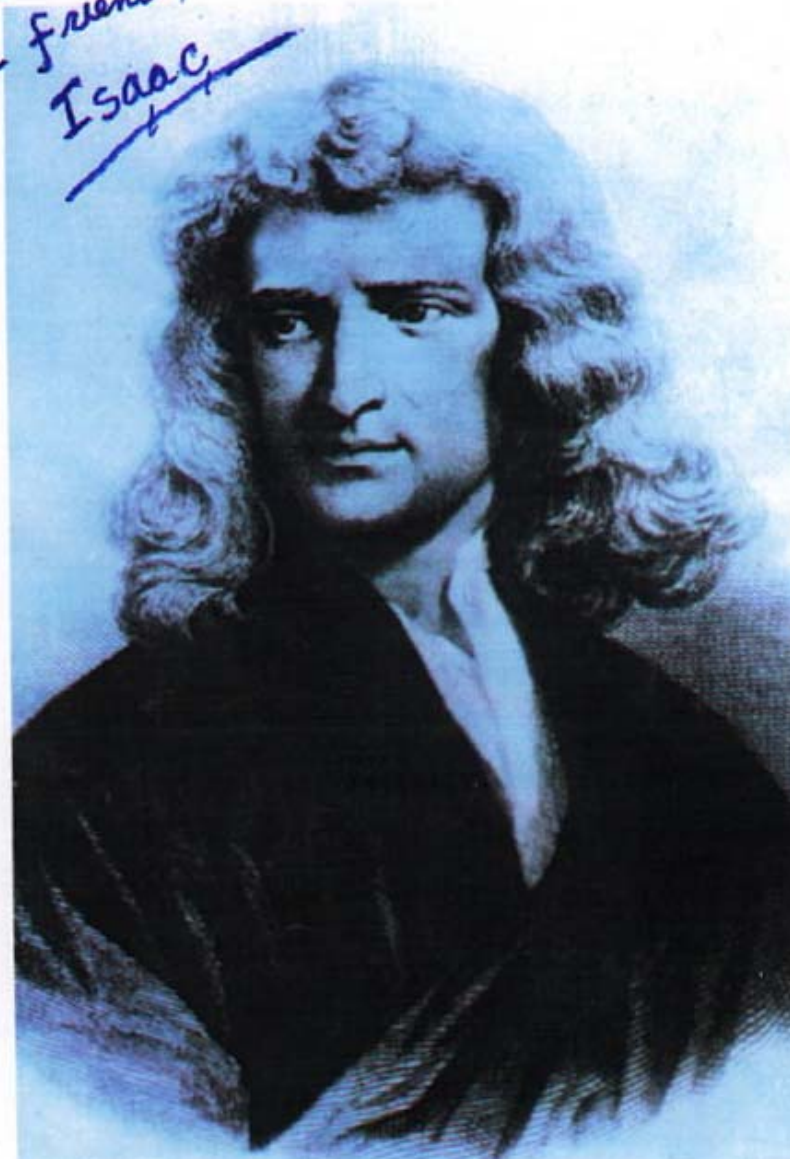
$$\Omega_i = \frac{\rho_i}{\rho_c}$$

Matter $\Omega_M \sim 0.3$

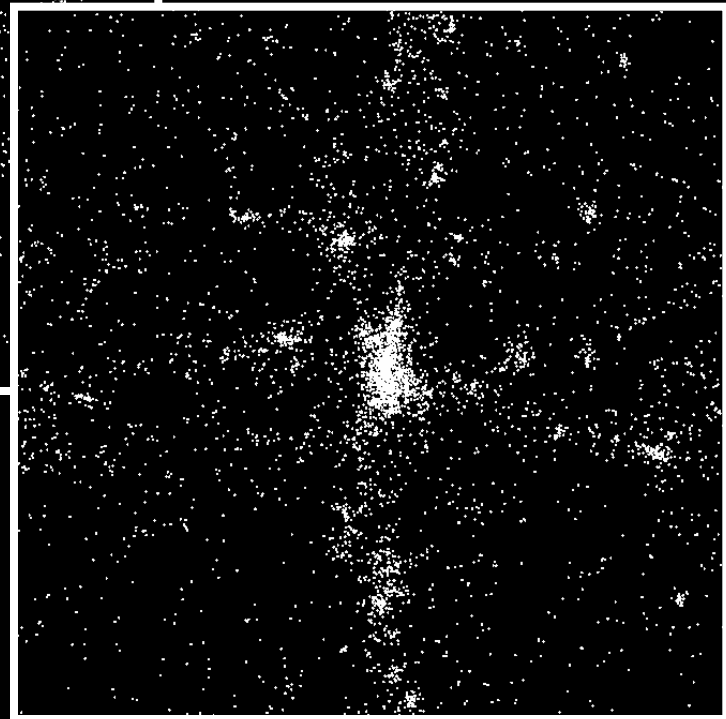
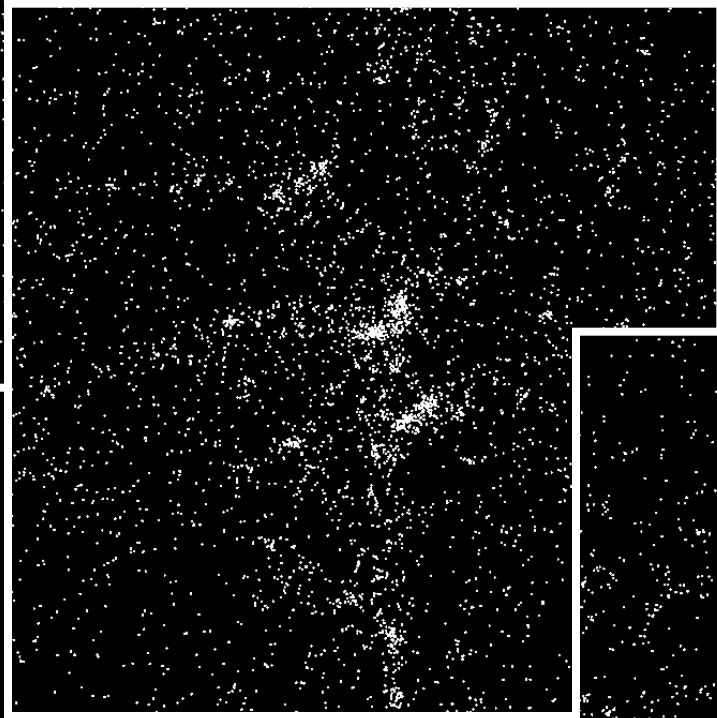
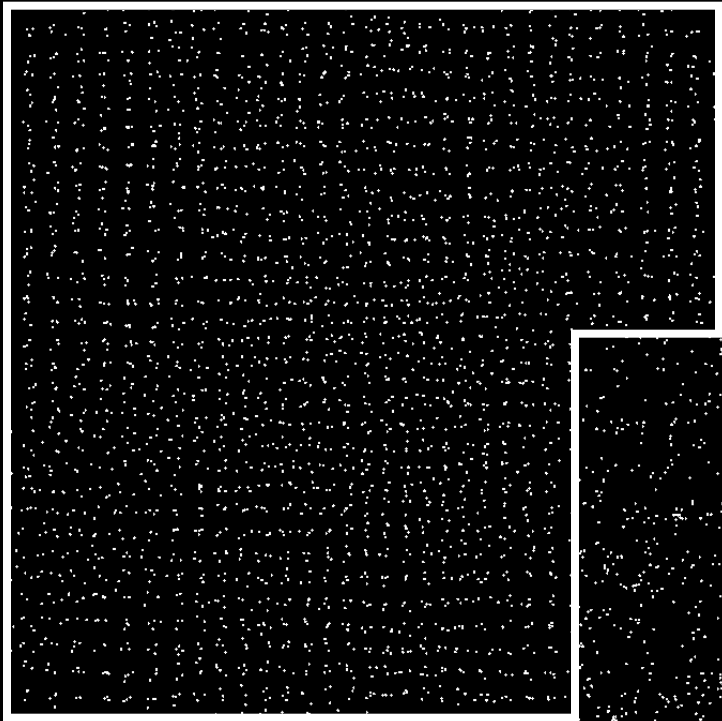


Gravitational instability

To Rocky,
Best wishes,
your friend,
Isaac



Structure grows

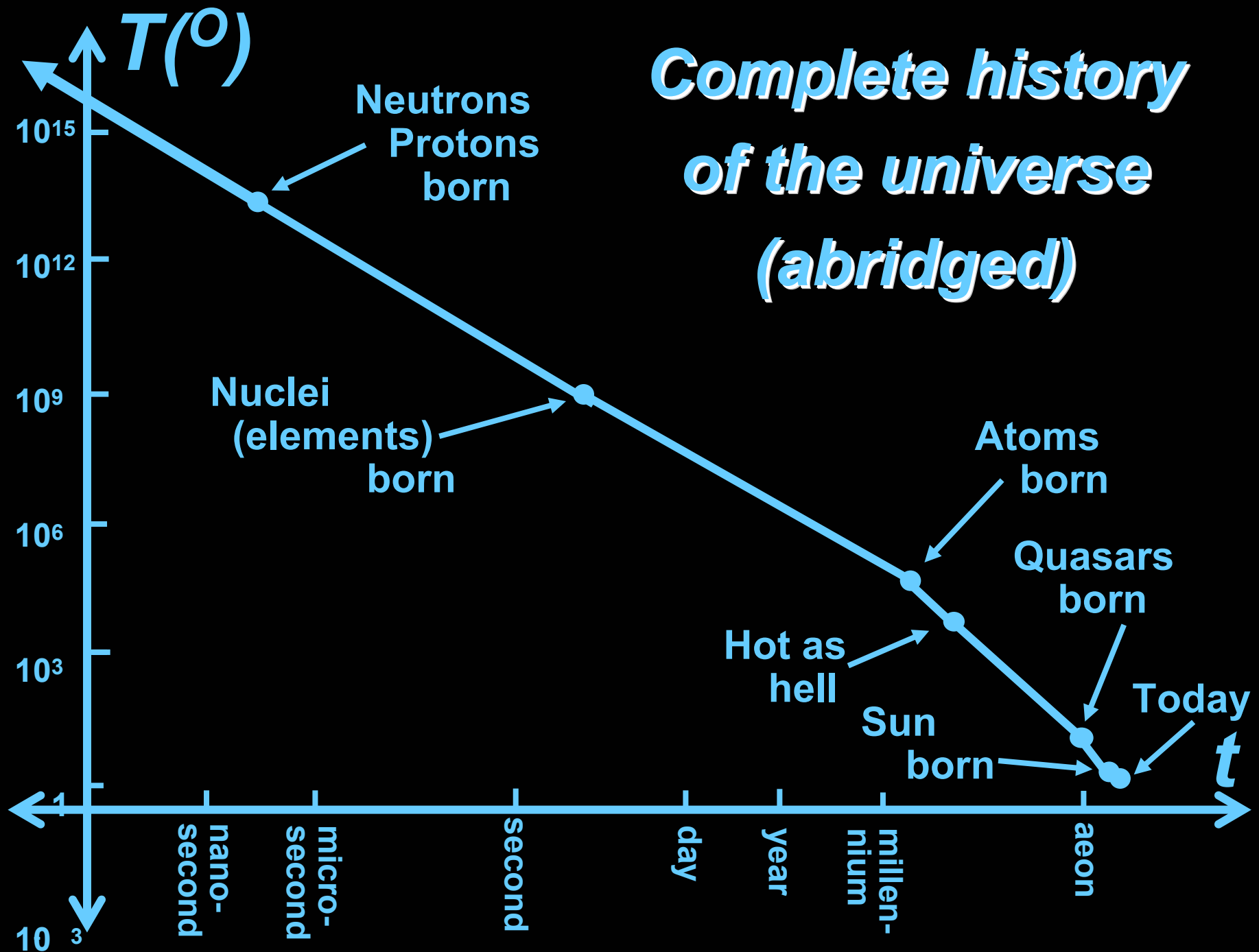


time ↘

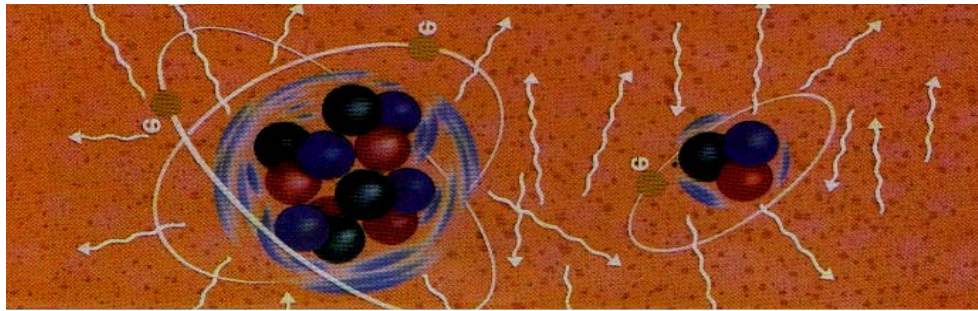
Most of the universe is dark!

It ain't even normal stuff!

Complete history of the universe (abridged)

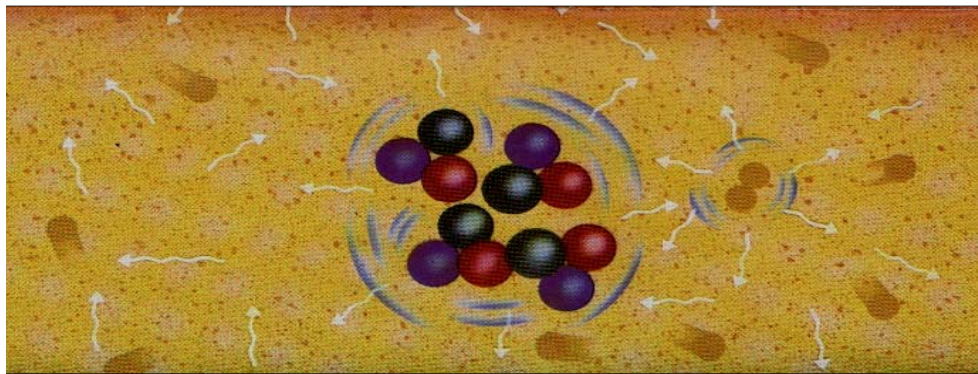


**380,000
years**



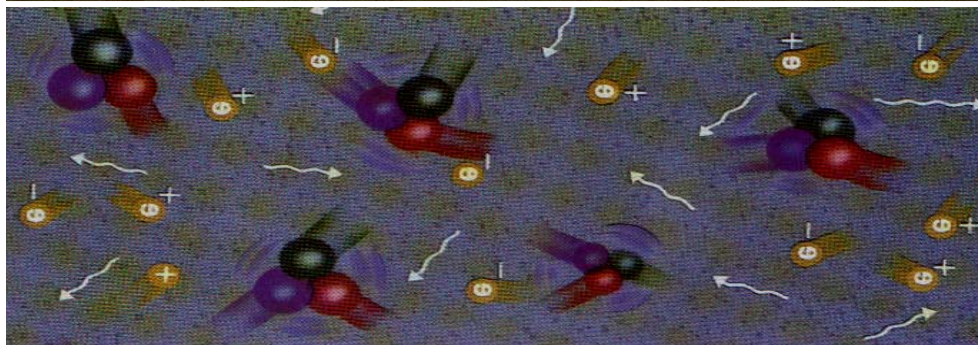
**atoms
form**

**3
minutes**



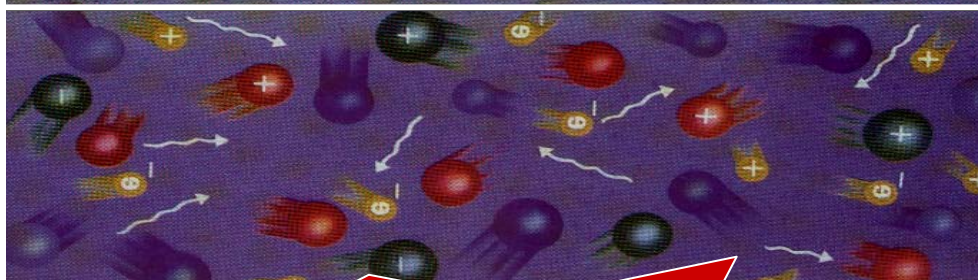
**nuclei
form**

**1-micro
second**



**neutrons
protons
form**

**4-pico
seconds**



**primordial
soup**

BANG!

Periodic table - chemist

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Periodic table - cosmologist

H

He

Metals

The Chemical Elements

Today:

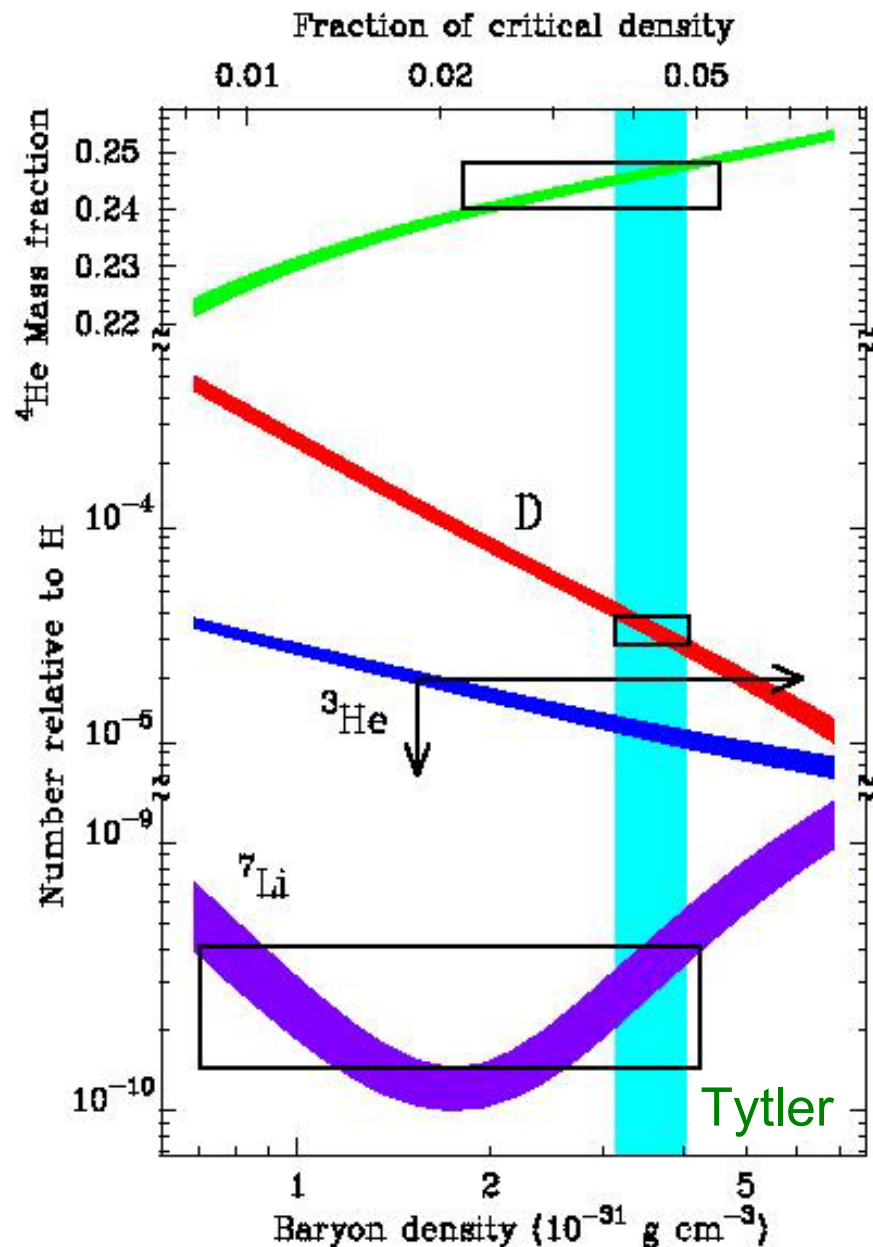
73%	Hydrogen	(10^{-5}	deuterium)
26%	Helium	(10^{-5}	^3He)
1%	Metals		

Three minutes AB:

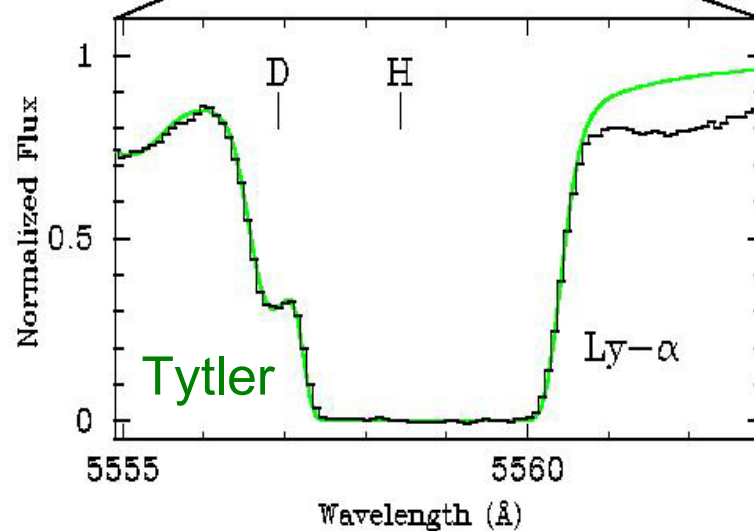
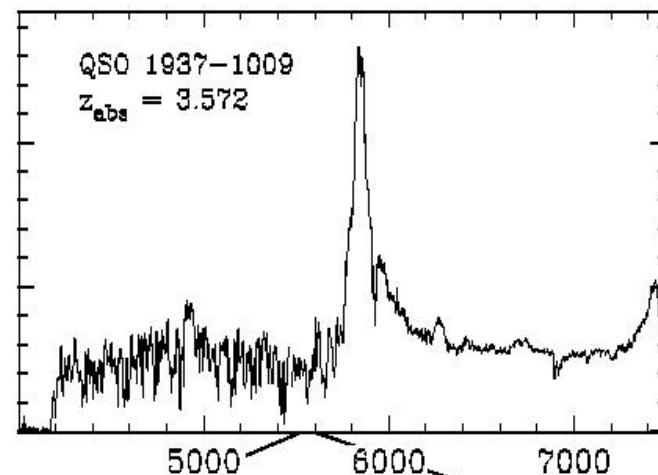
76%	Hydrogen	(10^{-5}	deuterium)
24%	Helium	(10^{-5}	^3He)
0.000000001%	Lithium		

Baryons $\Omega_B \sim 0.04$

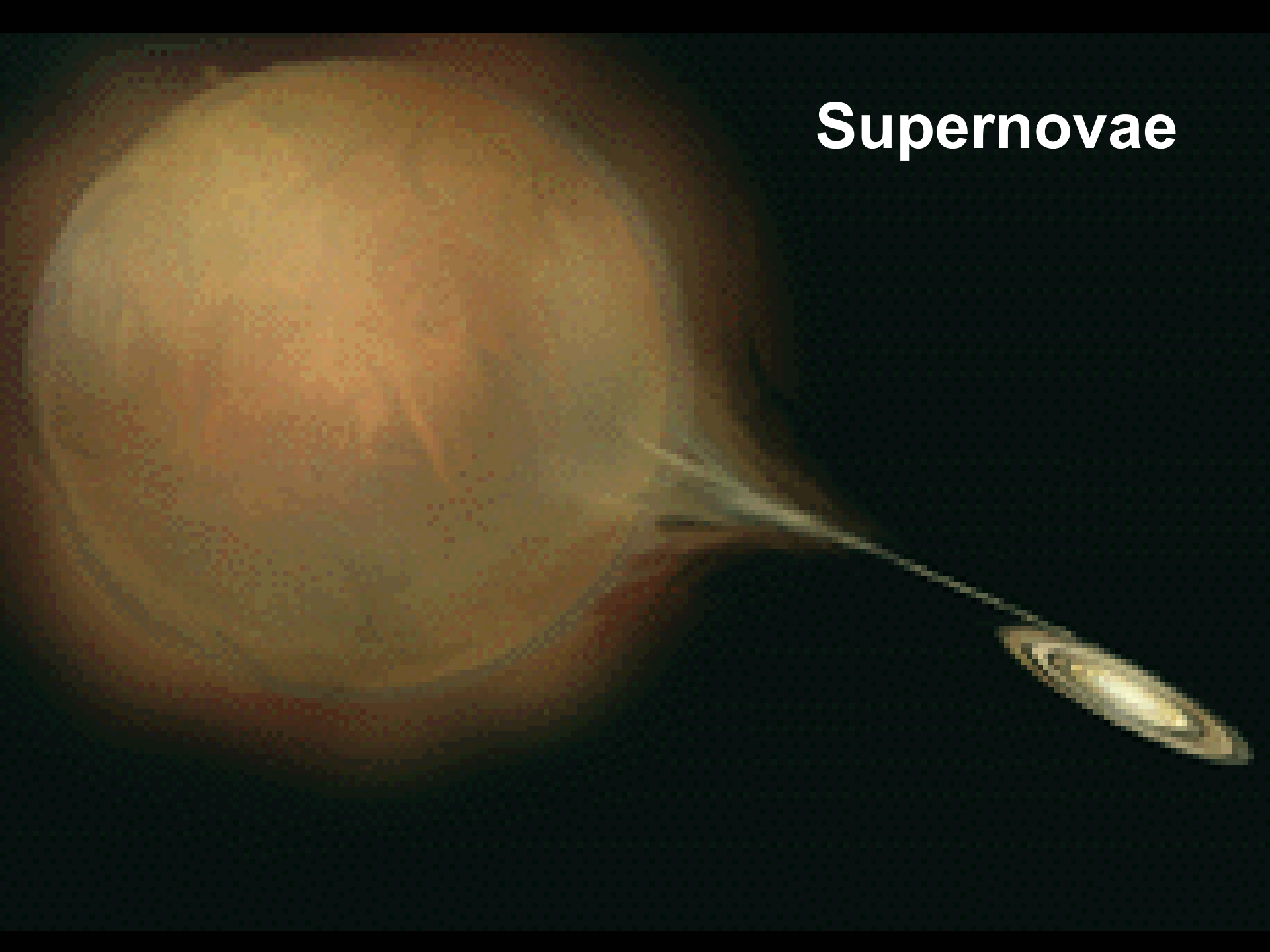
QSO 1937-1009



Flux ($10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$)

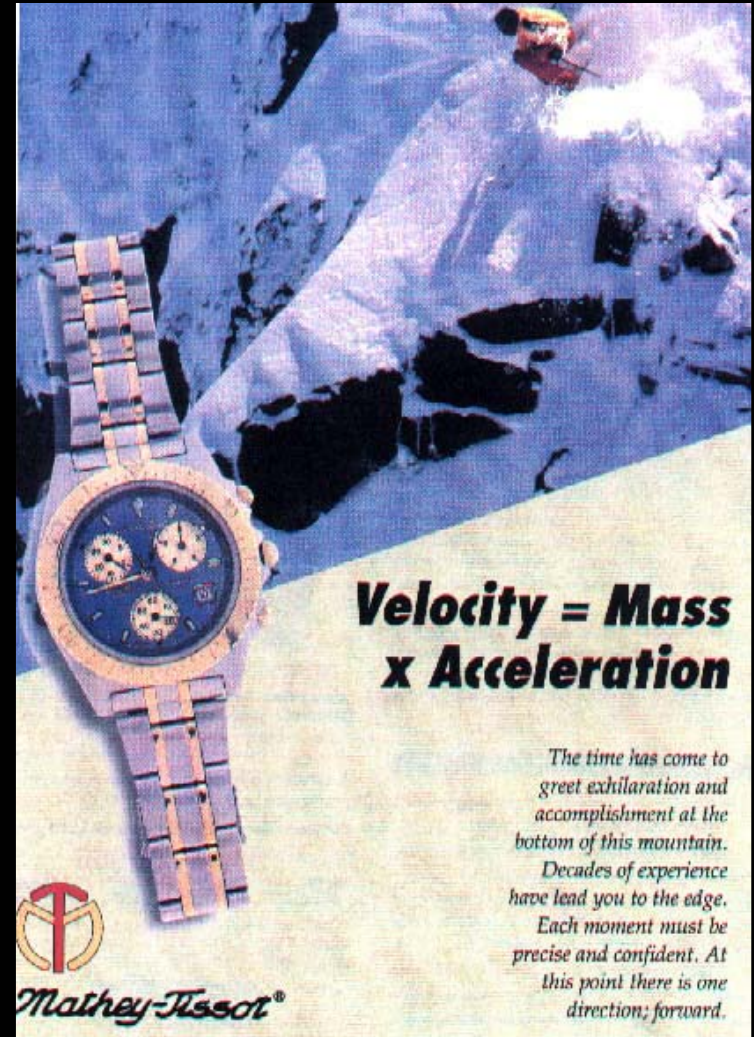


Supernovae



Dark matter?


- Modified Newtonian dynamics



The advertisement is a vertical rectangular image. The top half shows a diver in a red and white suit jumping from a rocky ledge into a body of water. The bottom half features a close-up of a Tissot Mathey-Tissot chronograph watch with a blue dial, three sub-dials, and a metal link bracelet. The watch is positioned diagonally. To the right of the watch, the text 'Velocity = Mass x Acceleration' is written in a bold, sans-serif font. Below this, a paragraph of text in a smaller, italicized font reads: 'The time has come to greet exhilaration and accomplishment at the bottom of this mountain. Decades of experience have lead you to the edge. Each moment must be precise and confident. At this point there is one direction; forward.' The Tissot logo, a stylized 'T' inside a circle, is located at the bottom left of the watch. Below the logo, the brand name 'Mathey-Tissot' is written in a cursive script.

**Velocity = Mass
x Acceleration**

*The time has come to
greet exhilaration and
accomplishment at the
bottom of this mountain.
Decades of experience
have lead you to the edge.
Each moment must be
precise and confident. At
this point there is one
direction; forward.*


Mathey-Tissot®

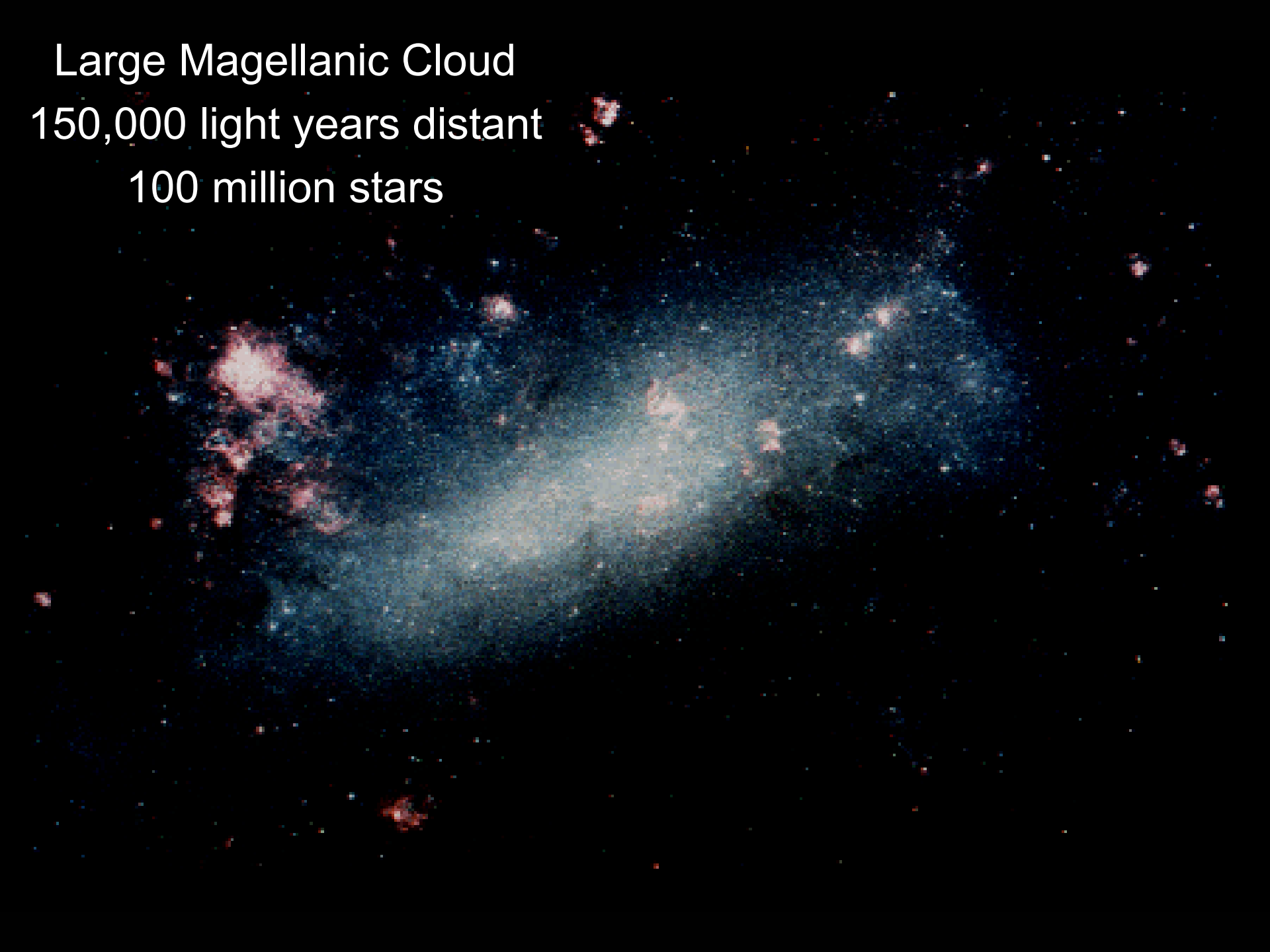
Dark matter?

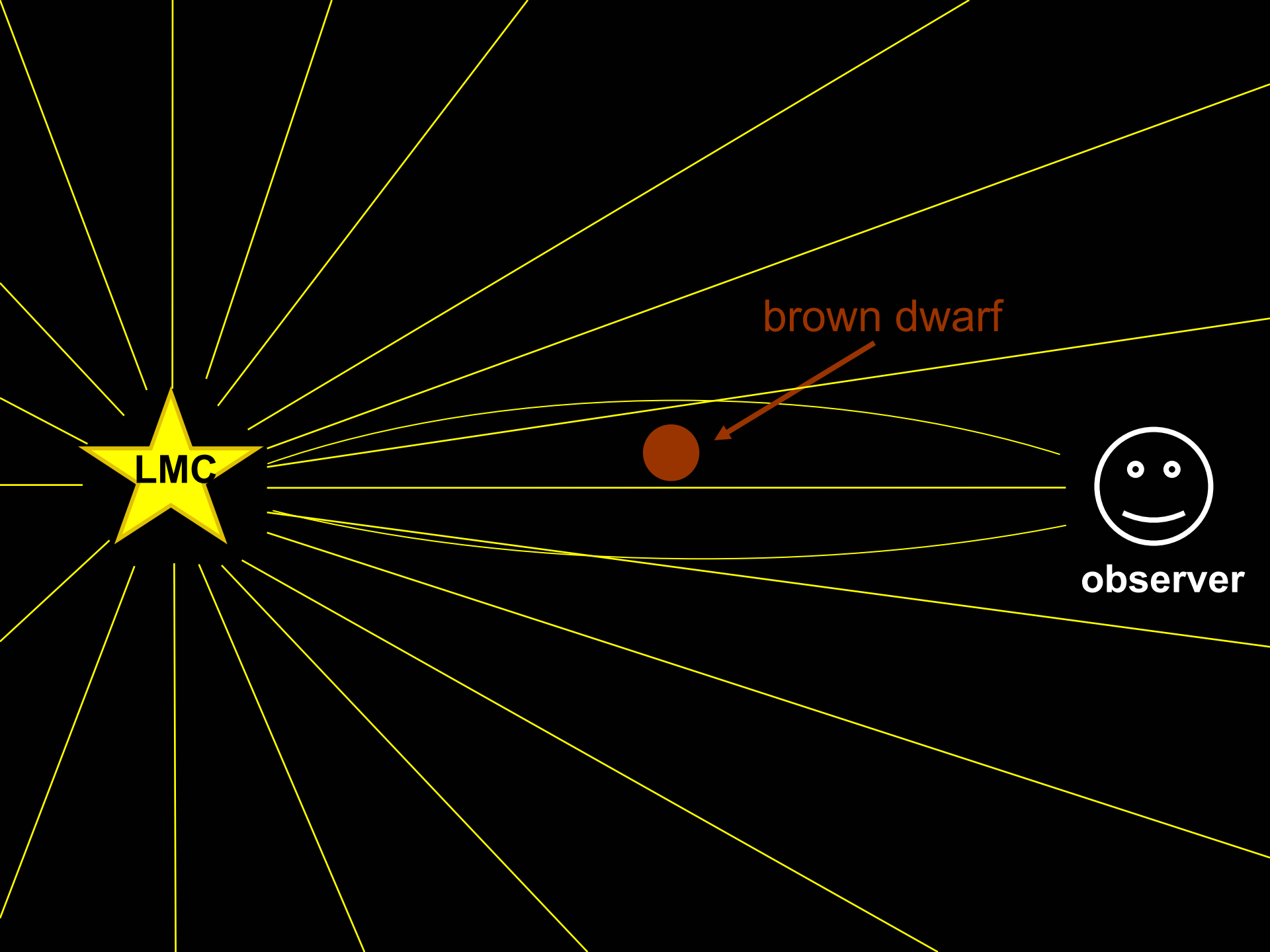
- Modified Newtonian dynamics
 - Planets
 - Mass disadvantaged stars
 - brown** **red** white
 - Black holes
- } **gravitational microlensing**

Large Magellanic Cloud

150,000 light years distant

100 million stars





LMC

brown dwarf

observer

Day 387.6

Day 392.4

Day 420.4

Day 425.5

Day 428.4

Day 430.5

Day 432.7

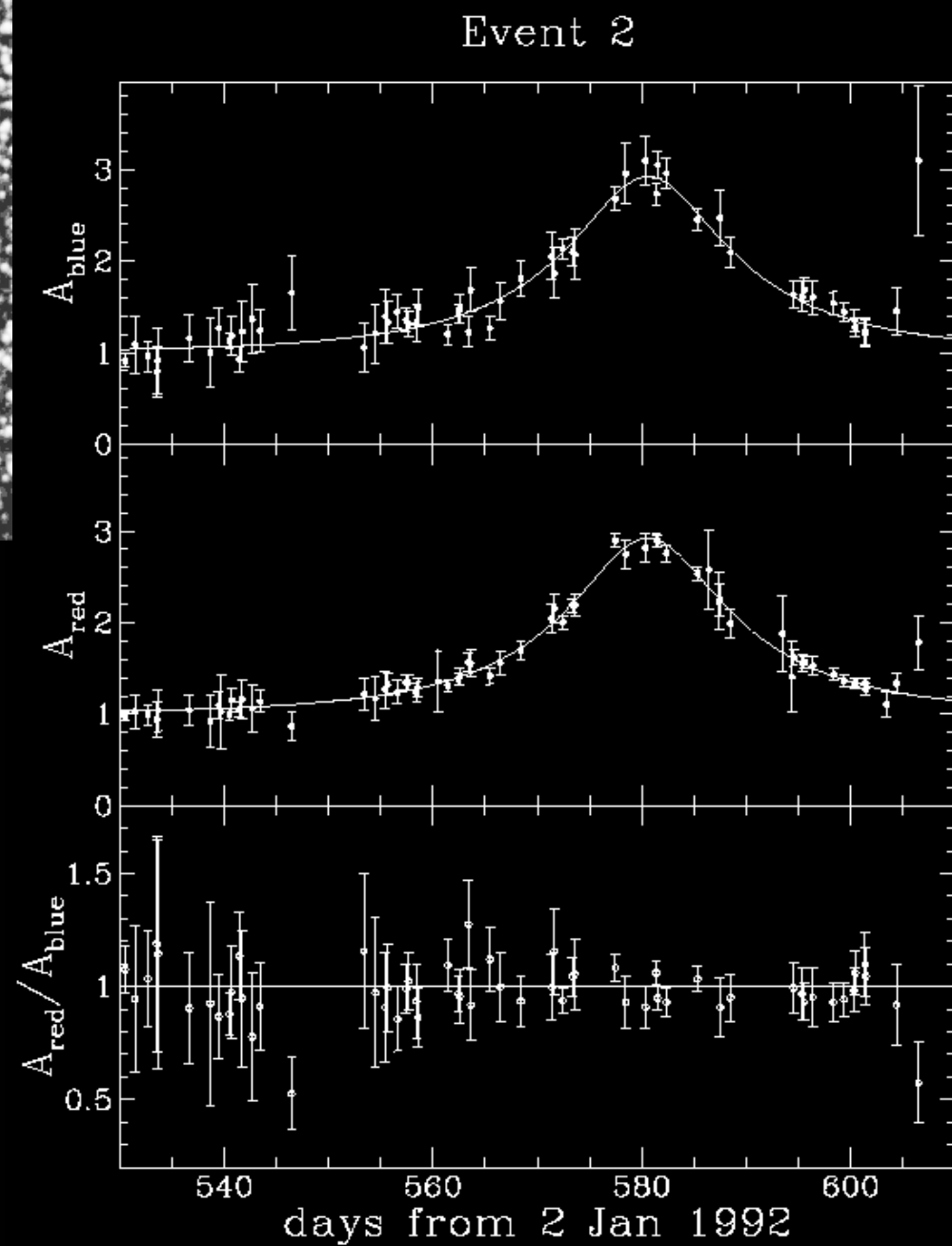
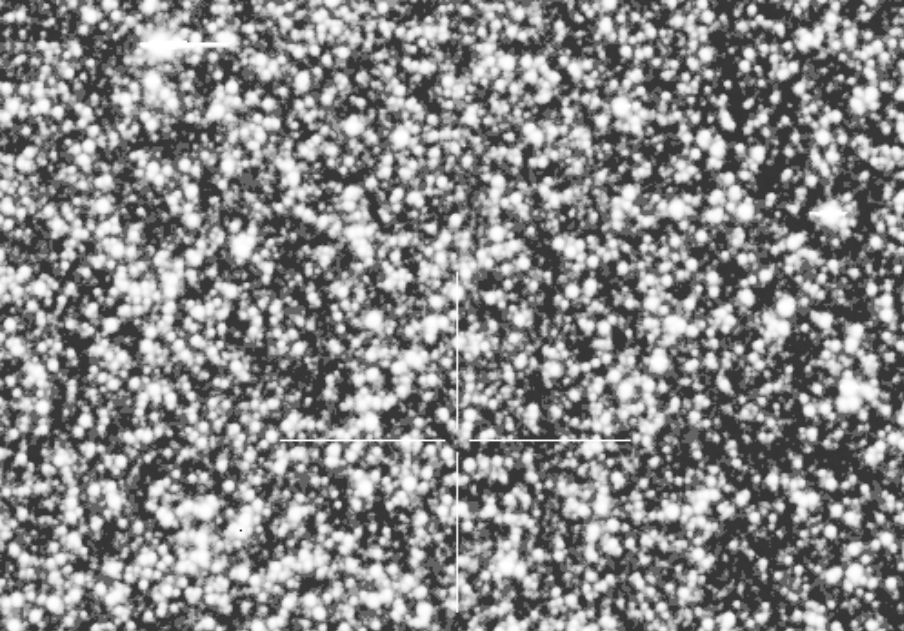
Day 435.4

Day 438.4

Day 442.6

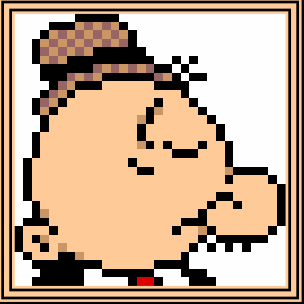
Day 457.5

Day 477.4

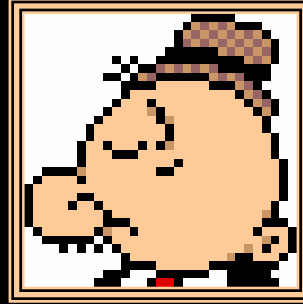


Most of the universe is dark !

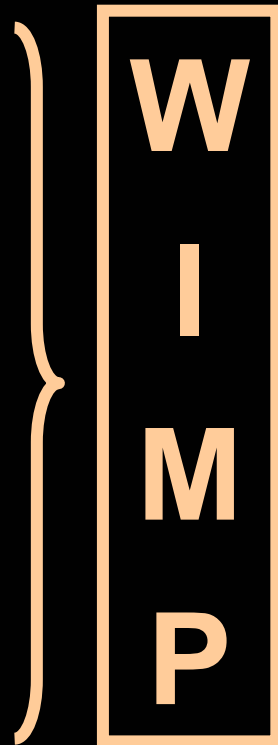
- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars
 - brown red white
- Black holes
- Fossil remnant of the big bang



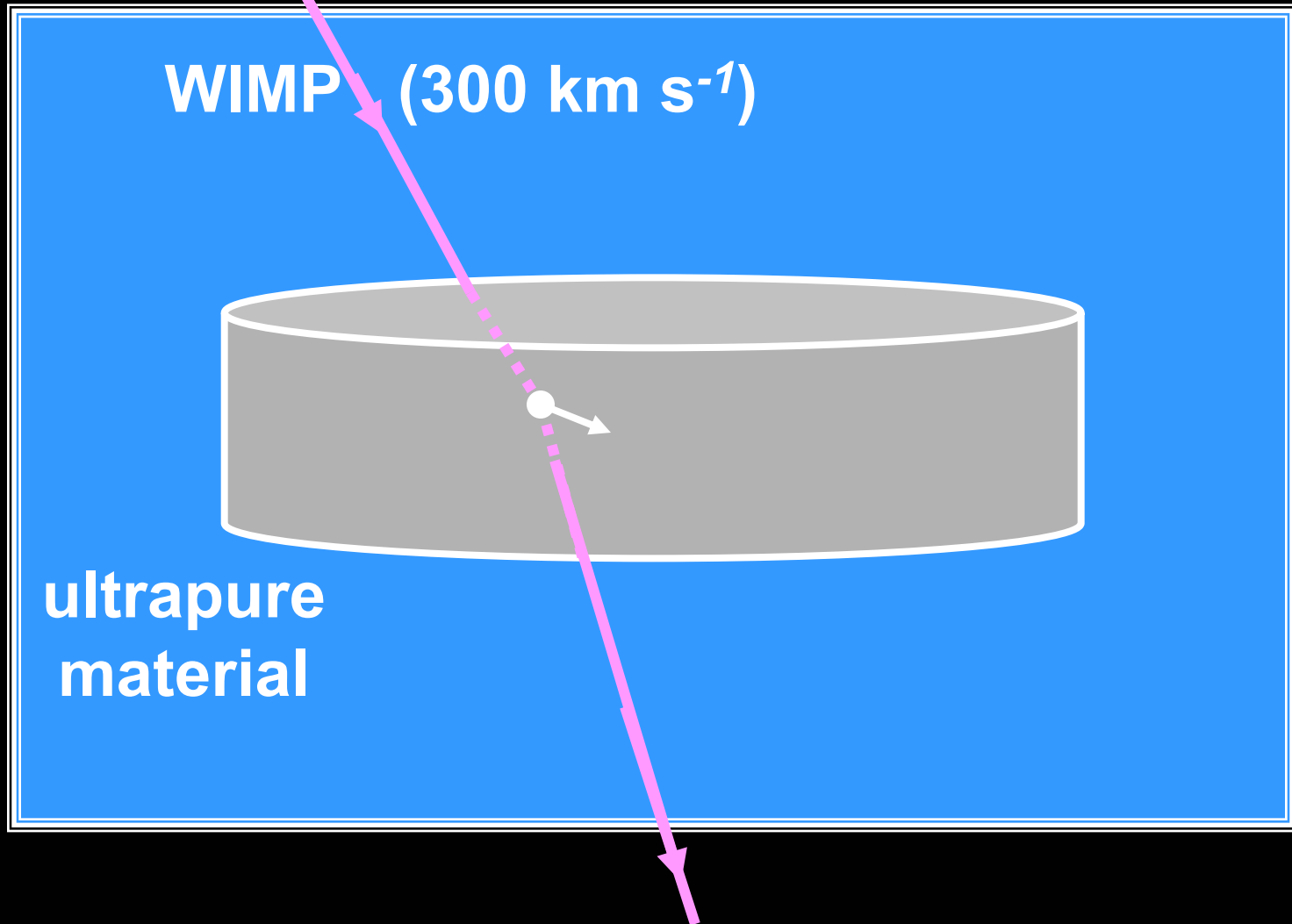
A WIMPY IDEA



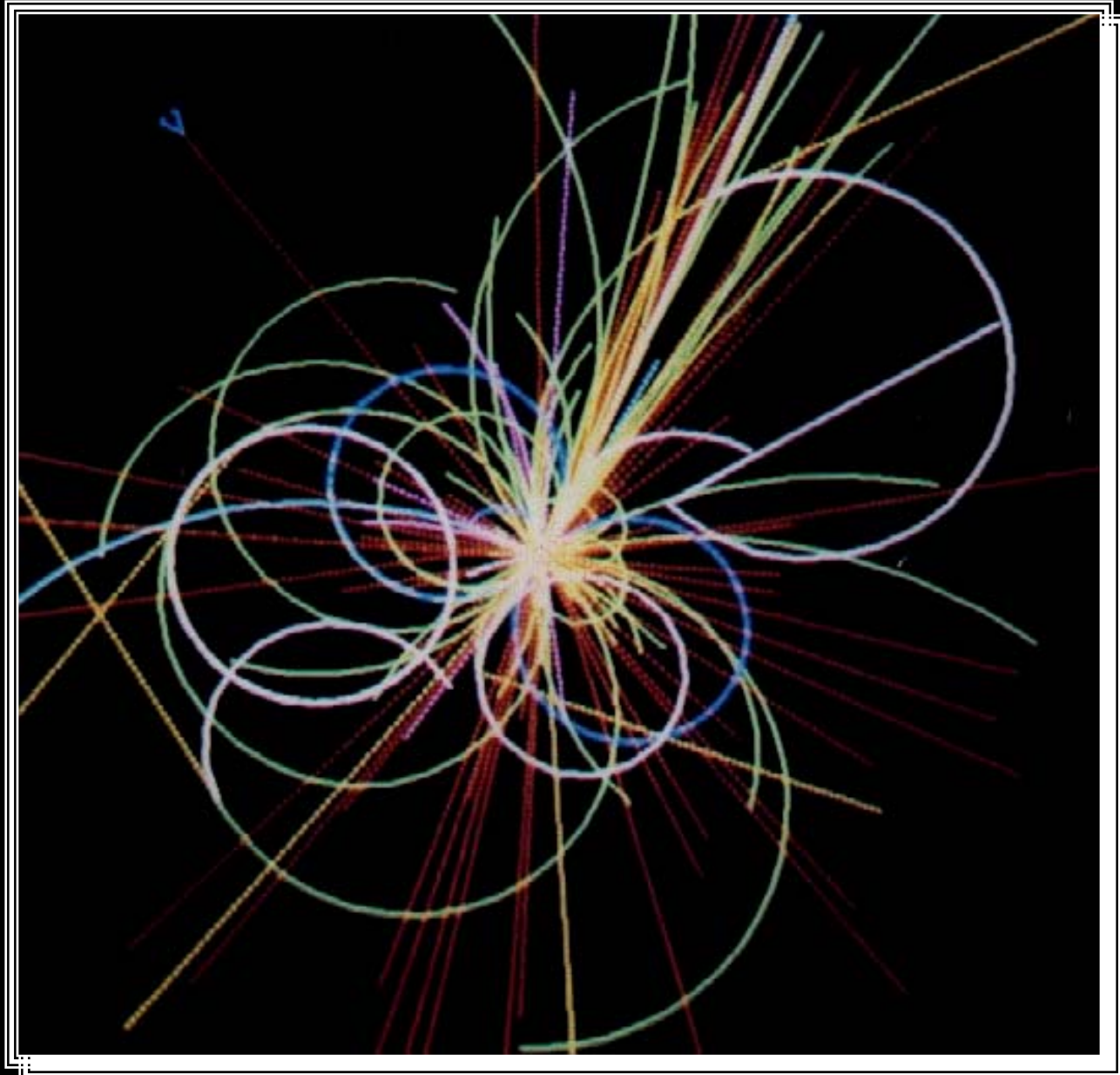
- Most of the universe is *invisible*
- Dominated by the rest mass of an elementary particle
 - present in the primordial soup
 - massive
 - neutral
 - weakly interacting
 - slow
 - stable



Direct detection



Make wimps in the laboratory



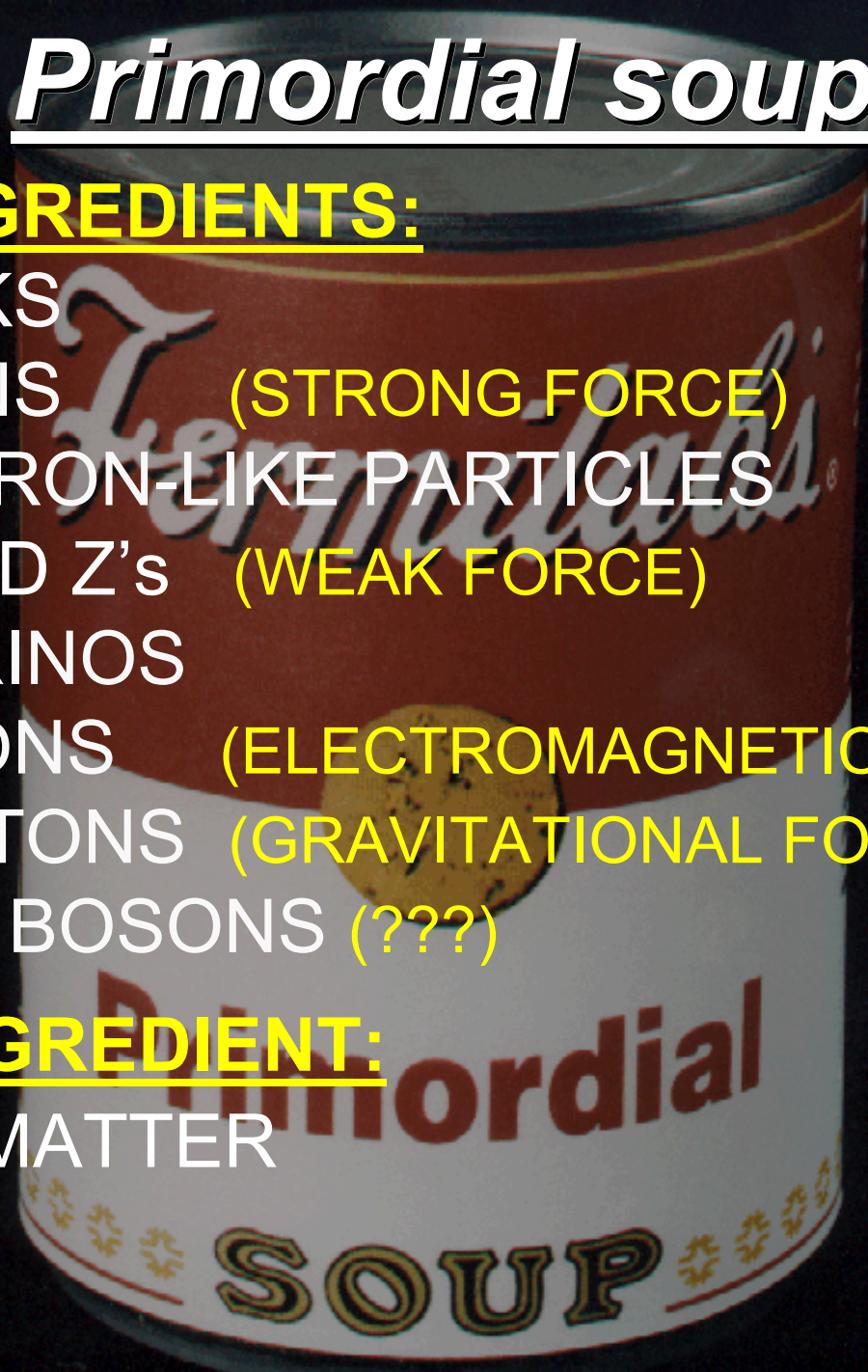
Primordial soup

KNOWN INGREDIENTS:

56% QUARKS
16% GLUONS (STRONG FORCE)
9% ELECTRON-LIKE PARTICLES
9% W's AND Z's (WEAK FORCE)
5% NEUTRINOS
2% PHOTONS (ELECTROMAGNETIC FORCE)
2% GRAVITONS (GRAVITATIONAL FORCE)
1% HIGGS BOSONS (???)

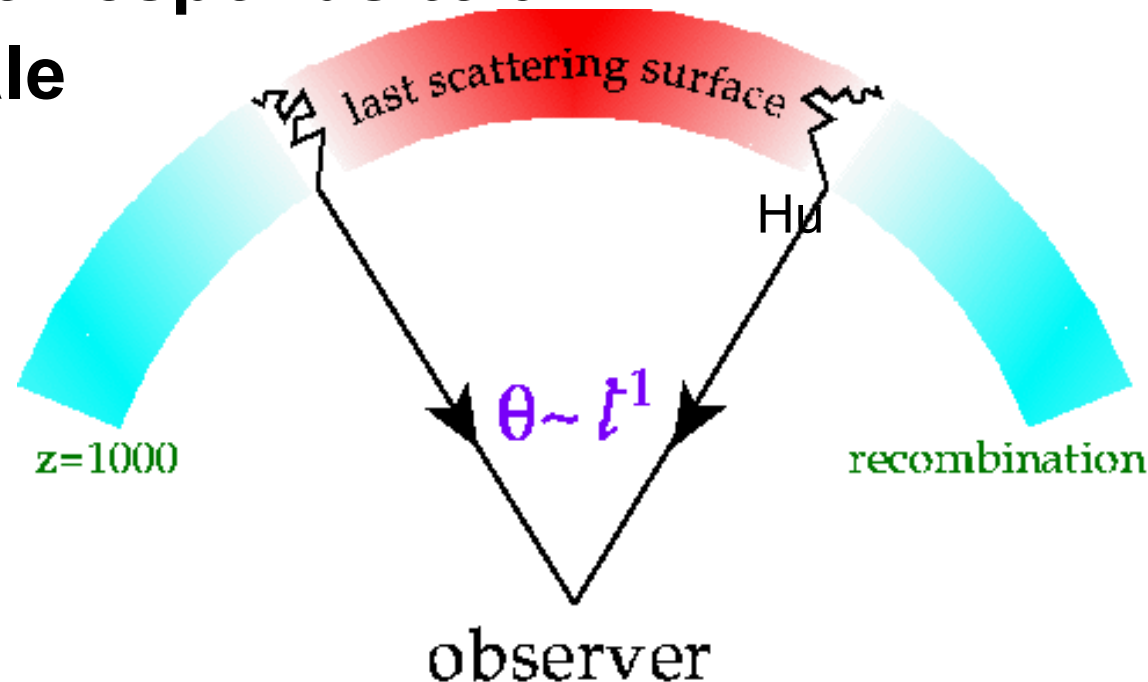
SECRET INGREDIENT:

DARK MATTER



Acoustic peaks

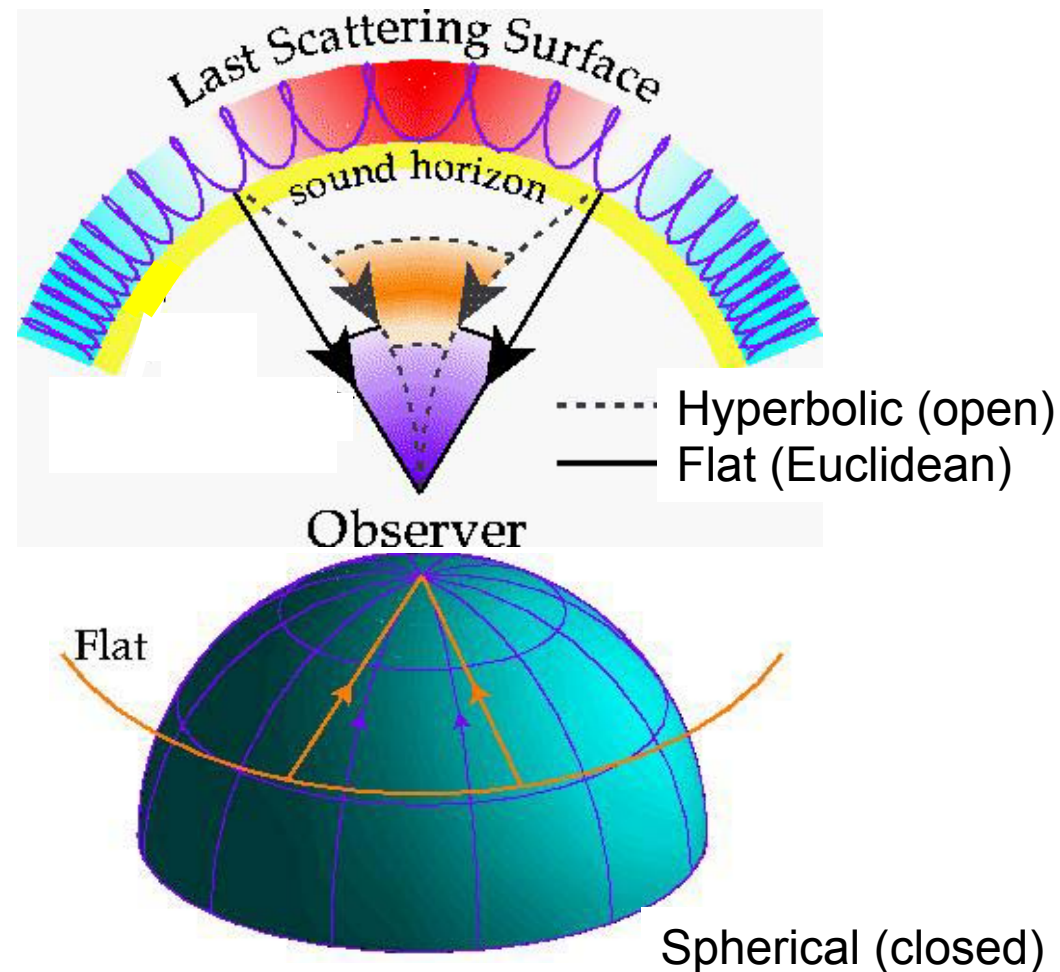
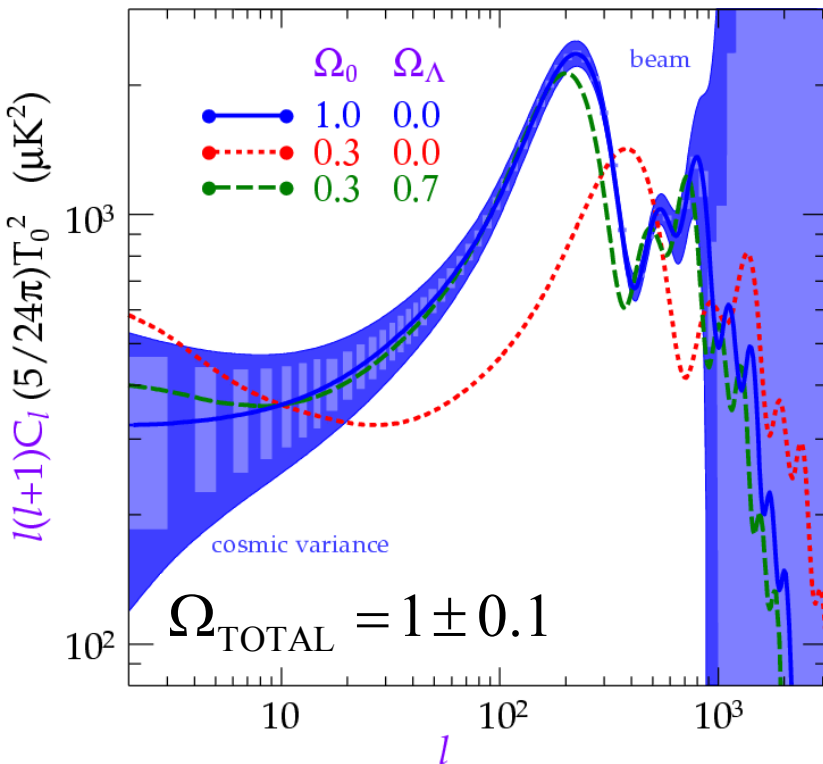
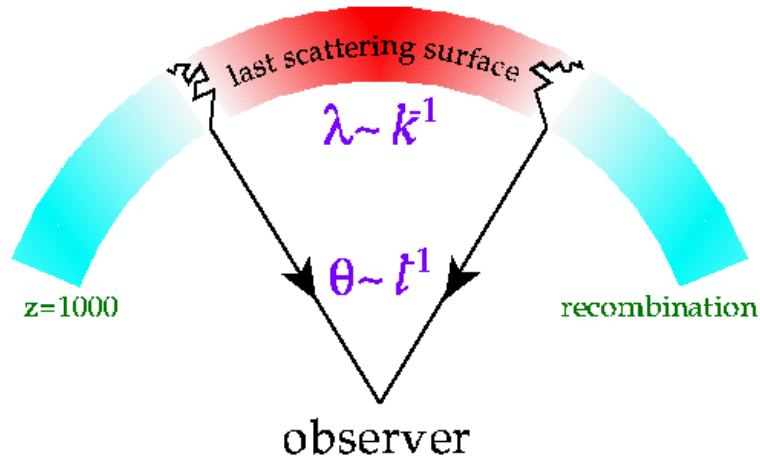
- At recombination, baryon–photon fluid undergoes “acoustic oscillations”
- Compressions and rarefactions change T_γ
- Peaks in ΔT_γ correspond to extrema of compressions and rarefactions
- Multipole number corresponds to a physical length scale



Acoustic peaks

Sound travel distance known

Observed $l_{\text{peak}} \sim \text{geometry}$



Dark energy?

Space and time are related.

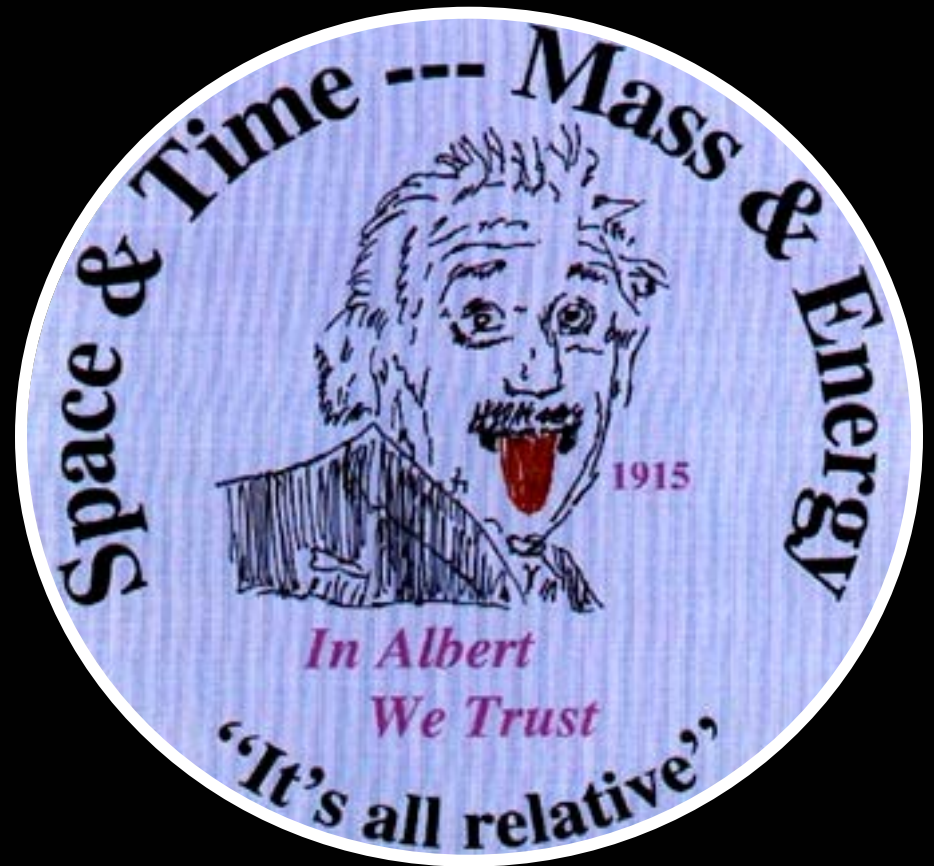
1905

Space is dynamical (curved, warped, bent).

1915

Empty space has a weight.

1917





the weight of space

Cosmological
constant

(Dark energy)

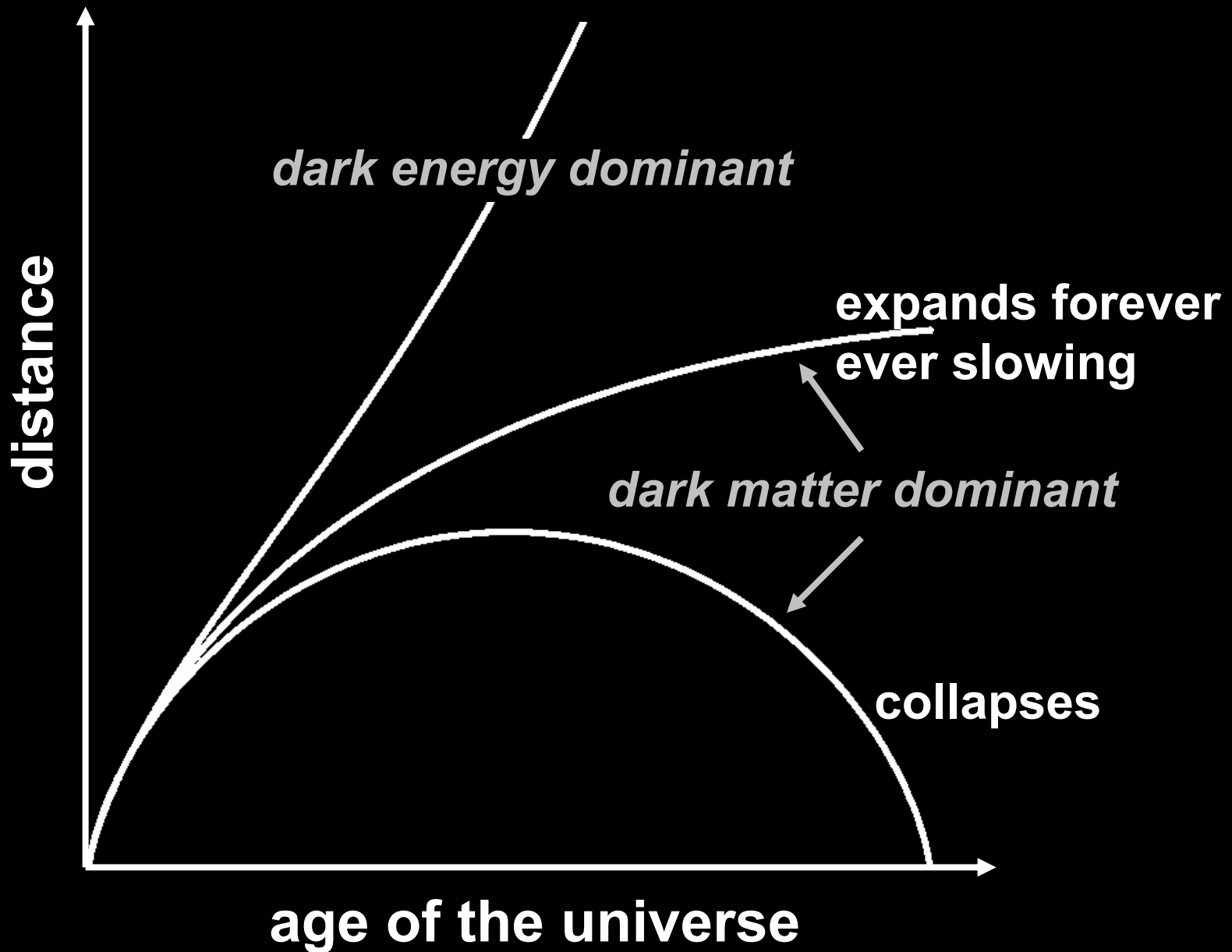
1917 Einstein proposed cosmological constant.

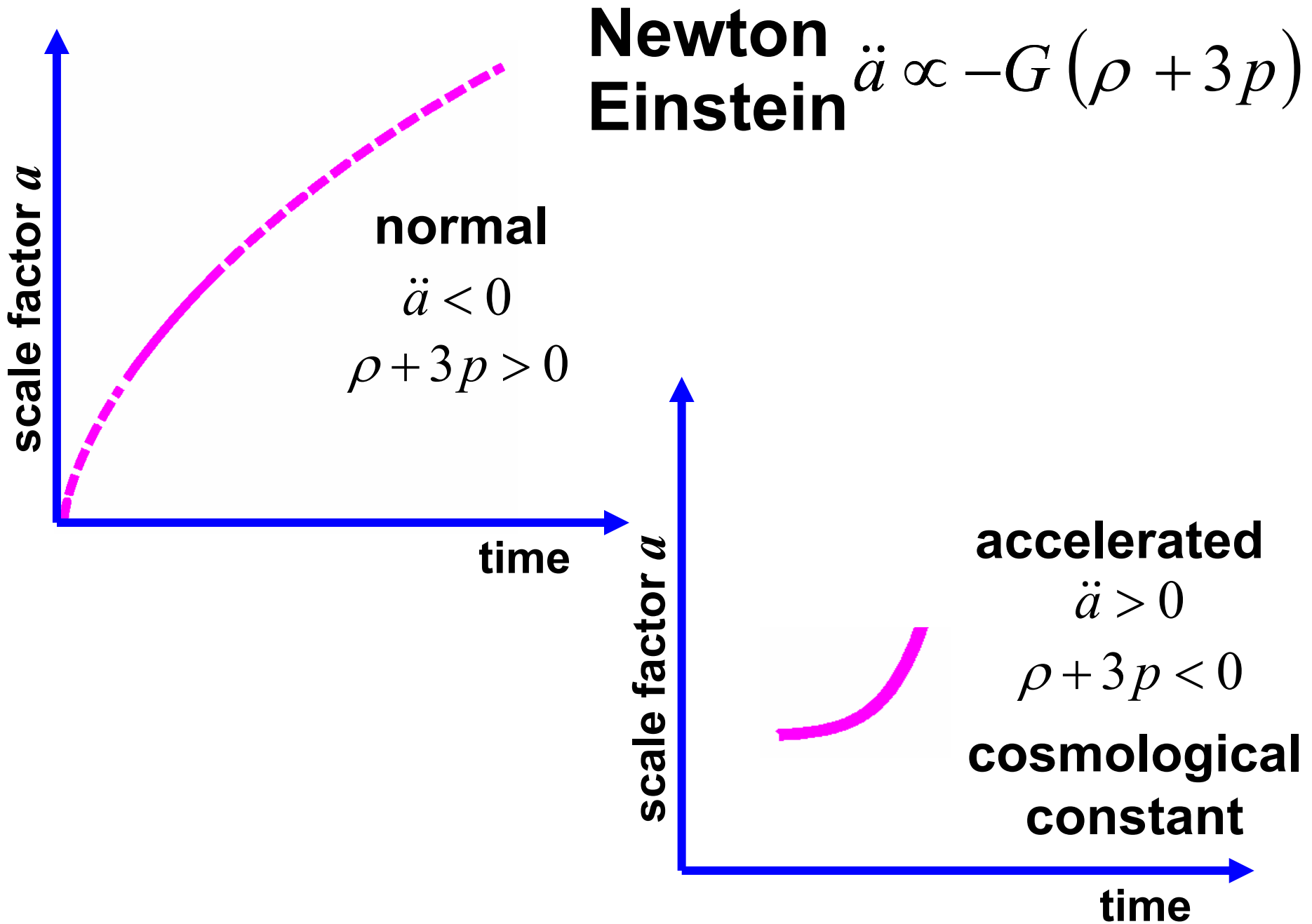
1929 Hubble discovered expansion of the Universe.

1934 Einstein called it “my biggest blunder.”

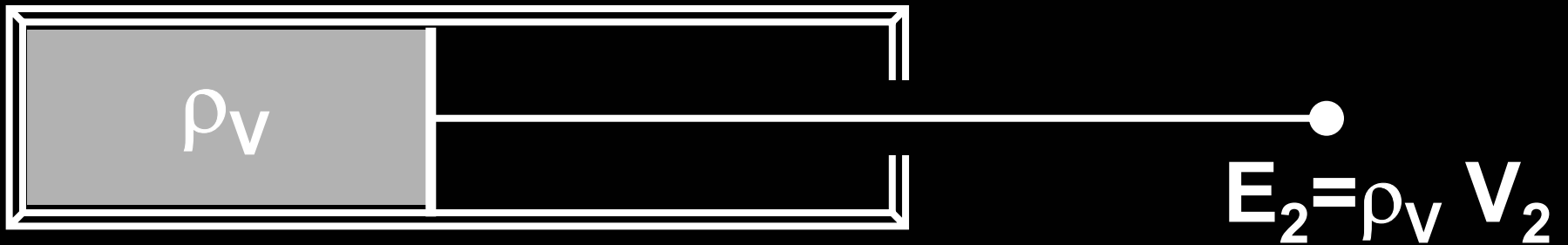
1998 Astronomers found evidence for it.

Cosmological constant (dark energy)





Vacuum pressure



$$E_2 > E_1$$

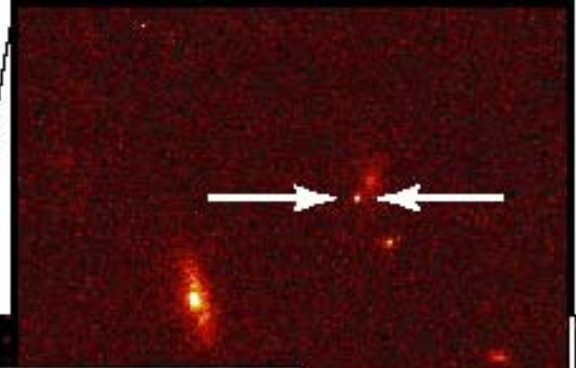
had to pull piston
“negative pressure”

SN 1987A in the LMC

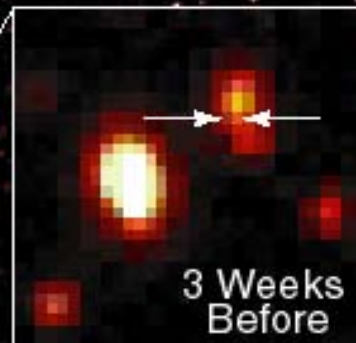
© Anglo-Australian Observatory



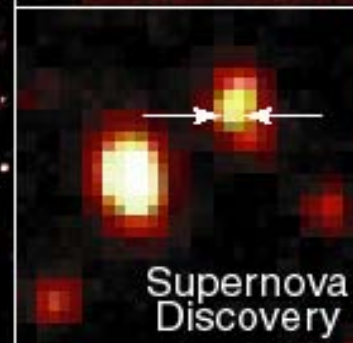
Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)



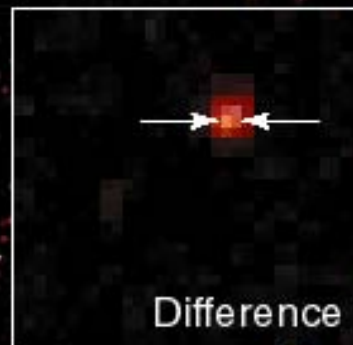
(as seen from
Hubble Space
Telescope)



3 Weeks
Before



Supernova
Discovery



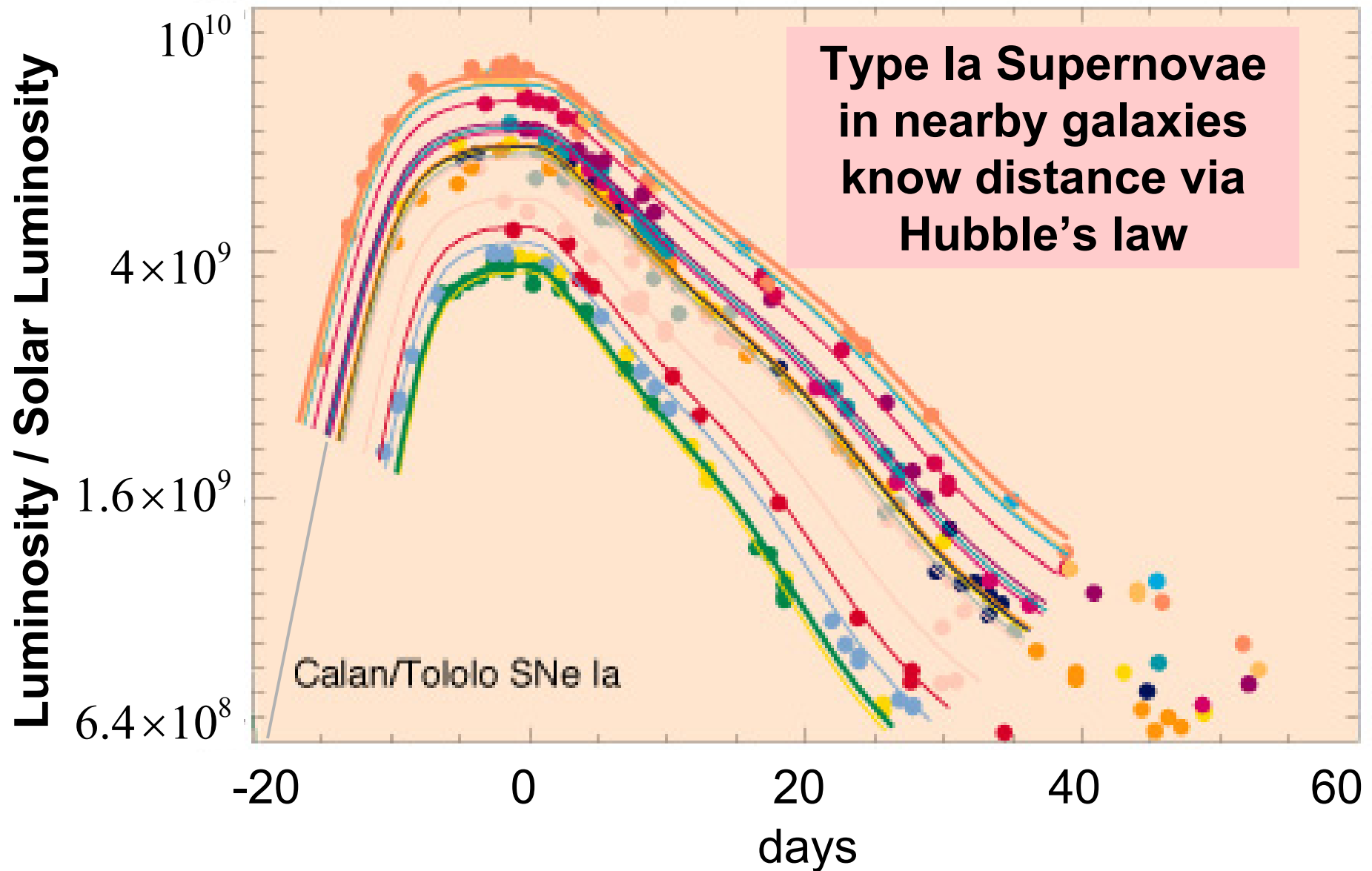
Difference

(as seen from
telescopes
on Earth)

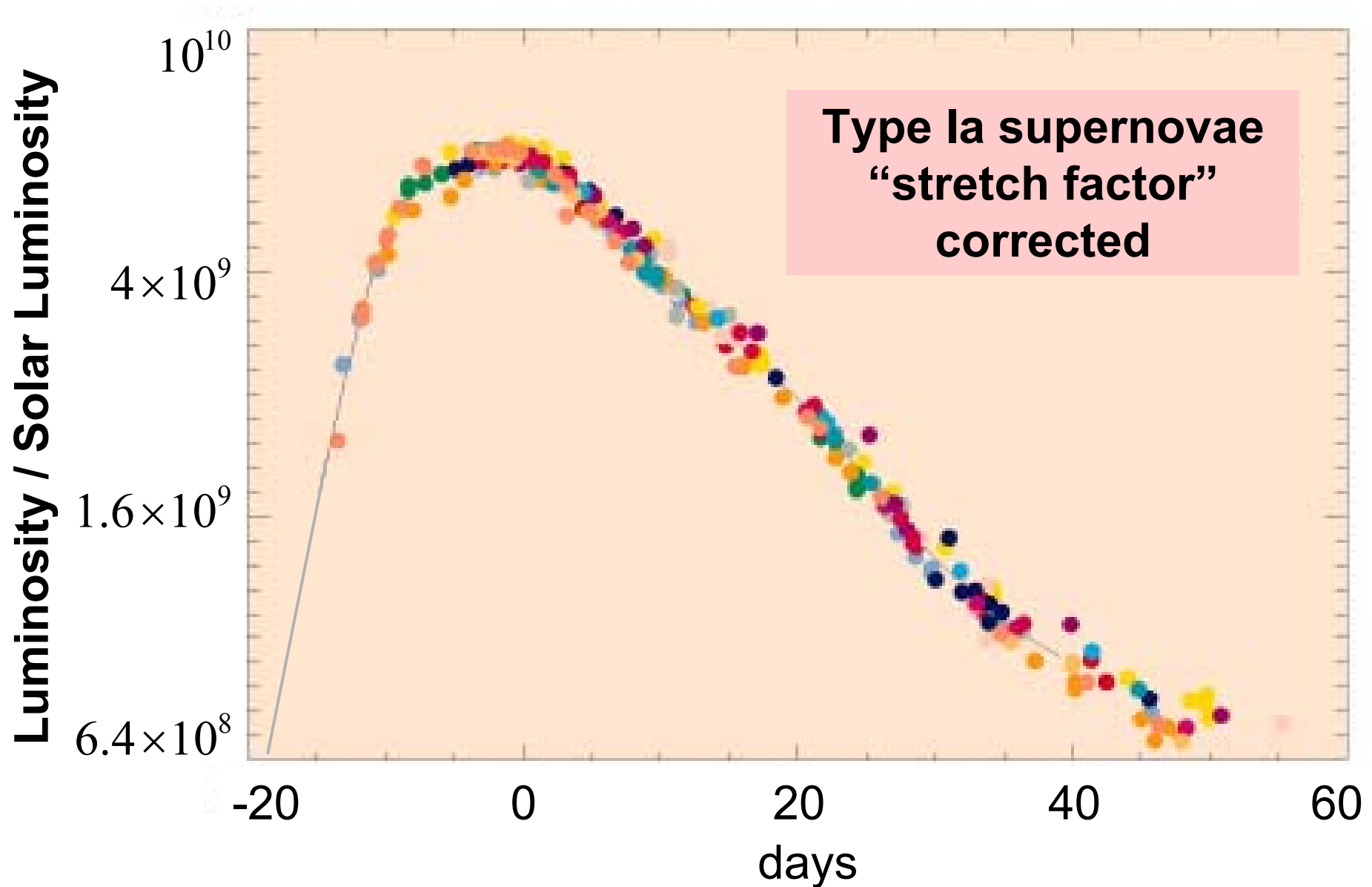


Centaurus A

Type Ia supernova are standard candles

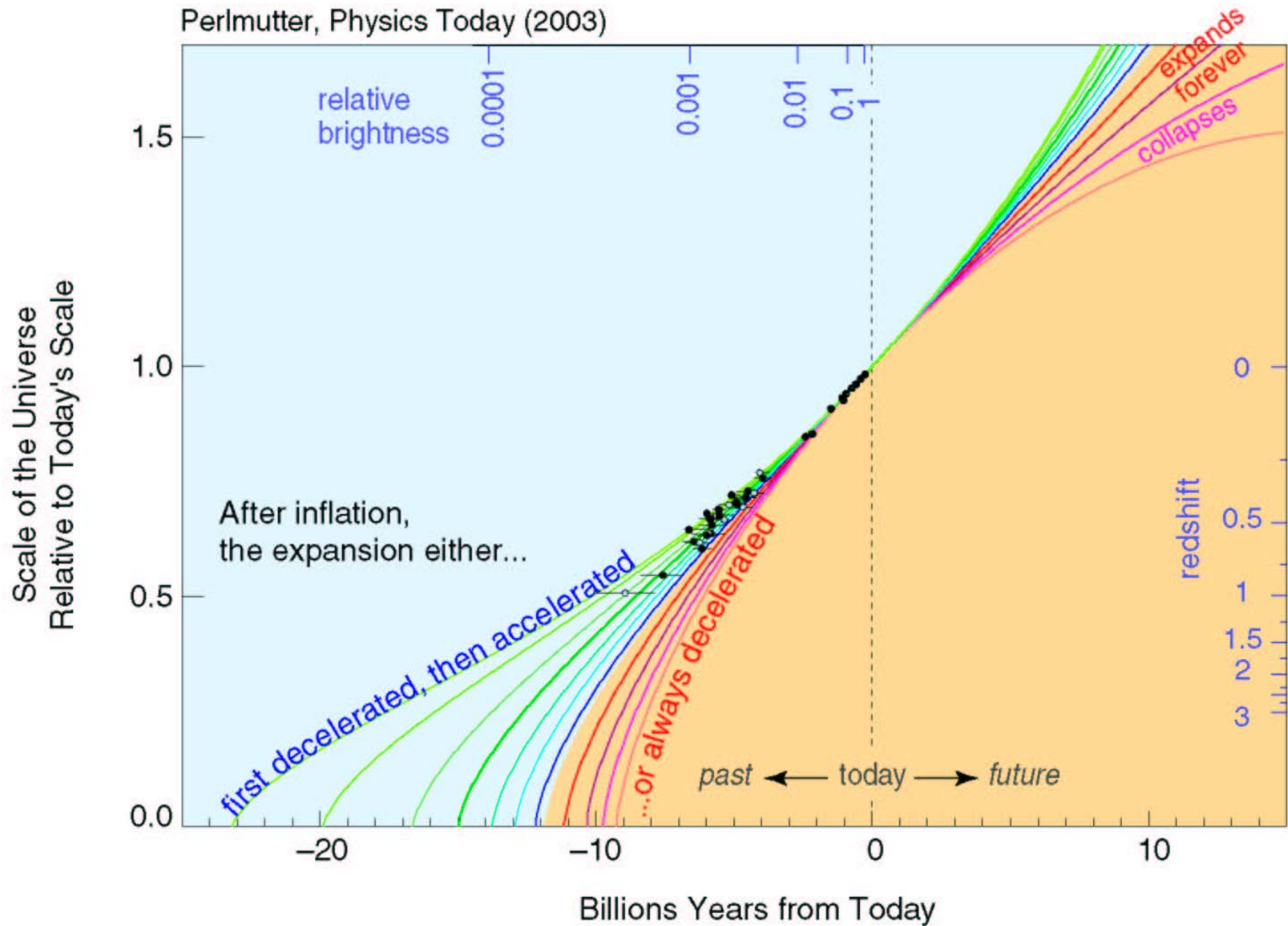


Type Ia supernova are standard candles

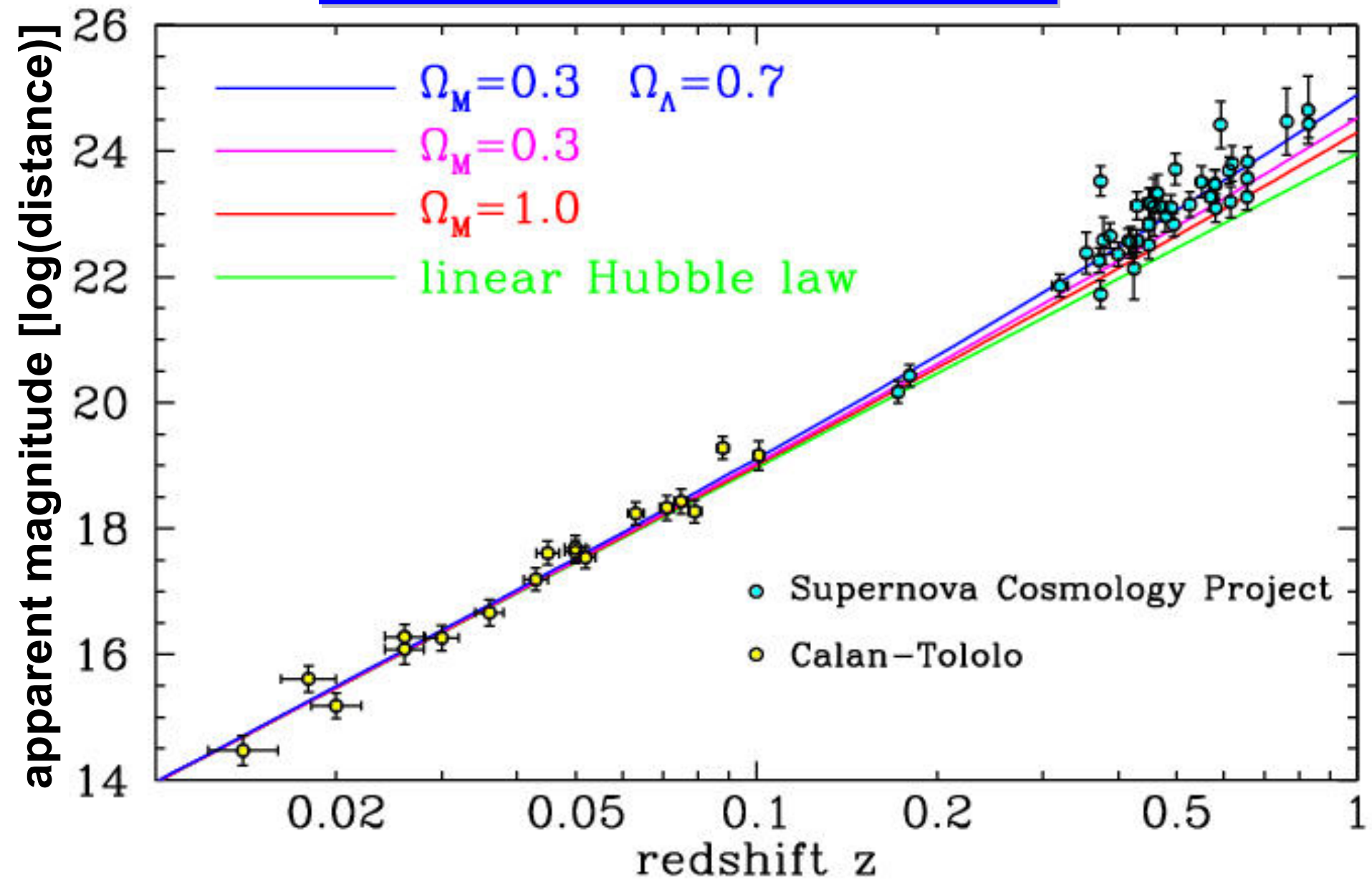


Expansion History of the Universe

Perlmutter, Physics Today (2003)



Type Ia supernova



Cosmological constant ***(Dark energy)***

Mass density of space: $10^{-30} \text{ g cm}^{-3}$

The unbearable lightness of nothing!

Cosmo-illogical constant?